Large perceptual distortions of locomotor action space occur in ground-based coordinates: Angular expansion and the large-scale horizontal-vertical illusion

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Abstract

What is the natural reference frame for seeing large-scale spatial scenes in locomotor action space? Prior studies indicate an asymmetric angular expansion in perceived direction in large-scale environments: Angular elevation relative to the horizon is perceptually exaggerated by a factor of 1.5, whereas azimuthal direction is exaggerated by a factor of about 1.25. Here participants made angular and spatial judgments when upright or on their sides in order to dissociate egocentric from allocentric reference frames. In Experiment 1 it was found that body orientation did not affect the magnitude of the up-down exaggeration of direction, suggesting that the relevant orientation reference frame for this directional bias is allocentric rather than egocentric. In Experiment 2, the comparison of large-scale horizontal and vertical extents was somewhat affected by viewer orientation, but only to the extent necessitated by the classic (5%) horizontal-vertical illusion (HVI) that is known to be retinotopic. Large-scale vertical extents continued to appear much larger than horizontal ground extents when observers lay sideways. When the visual world was reoriented in Experiment 3, the bias remained tied to the ground-based allocentric reference frame. The allocentric HVI is quantitatively consistent with differential angular exaggerations previously measured for elevation and azimuth in locomotor space.

Key words: distance perception, visual space, non-Euclidean, angular declination, spatial orientation

Large perceptual distortions in locomotor action space occur in ground-based coordinates:

Angular expansion and the large-scale horizontal-vertical illusion

We are effective at acting in the physical world, and this gives us confidence that our perceptual experience of the world is accurate with respect to its physical metric. However, there are known to be substantial and systematic biases in our perception of *locomotor spac*e. By locomotor space we refer the scale of space toward which walking and throwing, etc., are directed (e.g., the region about 2 to 50 m in front of us; see Cutting & Vishton, 1995[1]). Asked to estimate distance or slant, humans grossly underestimate distance (by 20-30%; Loomis & Philbeck, 2008) and overestimate hill slant (by 10-30°; Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Whereas it is frequently supposed that accurate actions depend on accurate perceptions, adaptation to prism goggles shows that, even when perception remains inaccurate, action can simply adapt (Harris, 1963). People who estimate that a target at 10 m is only 7 m away may nonetheless walk 10 m (accurately) to that target with their eyes closed (Loomis, Da Silva, Fujita & Fukusima, 1992) but perceive themselves to have walked only 7 m because perceived walked distance is calibrated to their visual experience (Durgin, 2014; Durgin, Fox & Kim, 2003; Durgin et al., 2005; Riemer, Hölzl & Kleinböhl, 2014). Similarly, hills also feel extremely steep underfoot (Hajnal, Abdul-Malak & Durgin, 2011). But why should evolution and development tolerate systematic error?

Several kinds of explanation of bias have been proposed previously, but very few address the issue of evolutionary adaptation. For example, in a paper arguing that hills appear even steeper as distance increases, Bridgeman and Hoover (2008) proposed that the misperception of things out of reach doesn't matter for action. Other views include the notion that the scaling of perceptual space may

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[1] In their classic chapter, Cutting and Vishton (1995) labeled this range "action space", as distinguished from "personal space" and "vista space". A limitation of this choice of labels is that a great many common actions (e.g., reaching, grasping, fine work) take place in "personal space". We therefore prefer "locomotor action space" or the shorter version, "locomotor space", to refer to this intermediate scale of space.

be fundamentally non-Euclidean (Foley, Ribeiro-Filho, & Da Silva, 2004; Gilinsky, 1951; Hecht, Van Doorn & Koenderink, 1999; Koenderink, van Doorn, Kappers, Doumen, & Todd; 2008; Norman, Crabtree, Clayton & Norman, 2005; Todd, Oomes, Koenderink & Kappers, 2001; Wagner, 1985), or that depth compression and slant overestimation along the line of sight may be due to reduced depth information (Palmisano, Gillam, Govan, Allison & Harris, 2010; Ross, 2008), or that perceived hill slant reflects behavioral potential, but doesn't affect action (Proffitt et al., 1995), or that biased estimates may be task specific (Kelly, Loomis & Beall, 2004; Loomis, Philbeck & Zahorik, 2002). In the present paper we sought to use parameter estimation as a way of testing the quantitative predictive value of a theoretical perspective that we have been developing lately (Durgin, 2014; Durgin & Li, 2011; Hajnal et al., 2011; Li & Durgin, 2009, 2010). This perspective argues that some of these biases may result from angular coding choices that serve specific informational goals of human action control systems, and thus are evolutionarily adaptive.

For example, directional visual variables used to control locomotor action might be densely coded in order to provide greater effective perceptual sensitivity for control (Durgin, 2014; Hajnal et al., 2011; Li & Durgin, 2009). Given that the sensitive control of action is normally tantamount for survival, this theory of dense angular coding provides an account of why systematic bias in the perception of space might be selected for by evolutionary processes. Angular variables are quite important for directing action, and we have observed that the perceived angular directions to locations along the ground (as well as to those not on the ground) are systematically exaggerated in the sagittal plane (the vertical plane that separates the right and left sides of the body). Thus, when asked to position a remote-controlled car so that it is half-way between straight ahead and straight down (i.e., at a 45° angle below straight ahead), participants tested at normal or artificially elevated eye-heights consistently set it in a direction that is only 30° below straight-ahead (Durgin & Li, 2011, Experiment 2). Many other types of measure also indicate that perceived angular deviations in elevation relative to straight ahead are exaggerated with a gain of 1.5 (e.g., Li & Durgin, 2009; Li, Phillips & Durgin, 2011). Angular declination is a potent source of information about distance along the ground (Gajewski, Philbeck, Wirtz, & Chichka, 2014; Messing & Durgin, 2005; Ooi, Wu & He, 2001; Wallach & O'Leary, 1982; Williams & Durgin, 2015), and angular exaggeration with a gain of 1.5 can account quite well for the systematic underestimation of ground distance described above for explicit distance estimation. Note that angular expansion (rather than distance contraction, per se) is consistent with dense coding for greater coding sensitivity in the control of action by angular variables.

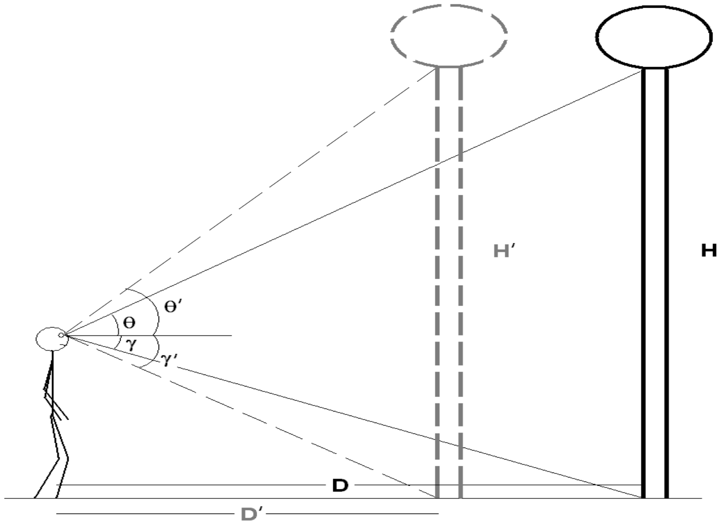

Figure 1. Diagram showing how egocentric distance underestimation (D') and misperception of the height/distance ratio (H/D) can be understood in terms of visual direction: The exaggeration of perceived elevation relative to straight ahead (with a gain of 1.5) foreshortens perceived ground distance relative to eye-height.

As an early test of this idea, we asked people to set themselves the same distance from a pole as the pole was high and found that performance in this task, both in our lab and in a prior report by Higashiyama and Ueyama (1988, Experiment 3), was extremely well predicted by assuming an angular exaggeration of perceived elevation (or declination) with a gain of 1.5 (Li, Phillips & Durgin, 2011), such as we had measured previously (Durgin & Li, 2011). The perception of space in this task can be represented by a diagram like that shown in Figure 1. The gain in perceptual sensitivity based on such a systematic distortion is analogous to that obtained by using a magnifying glass to help do fine work. In the present paper we will ask if this exaggerated angular bias, as assessed by vertical/horizontal angular bisection, and by height-distance matching, is yoked to a retinotopic cortical representation or to the external reference frame of the ground plane. We expected that these angular variables might be tied to the reference frame of the horizontal ground plane.

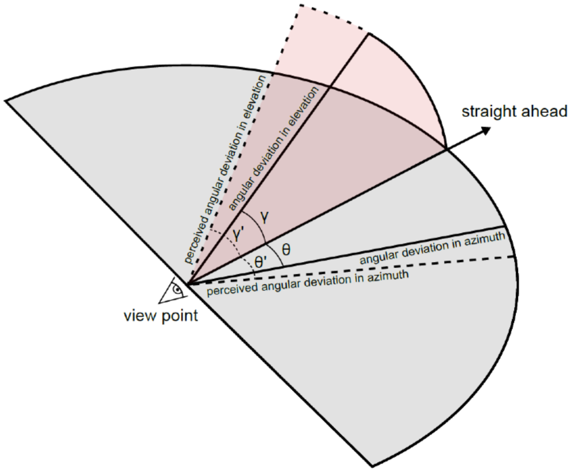

Figure 2. Diagram illustrating the differential angular expansions in elevation (1.5 gain) and azimuth (1.25 gain) that have been measured in large-scale spaces.

Although there also appears to be angular exaggeration in perceived direction to the left and right in locomotor space[2] (Foley et al., 2004; Higashiyama, 1992; Li, Sun, Strawser, Spiegel, Klein, & Durgin, 2013), the left/right angular bias typically observed is much smaller than that in the vertical direction (i.e., 1.25, rather than 1.5, Li & Durgin, submitted). A depiction of the differential expansion in azimuth and elevation is shown in Figure 2. In Experiment 1 we compared the perceptions of upright observers with those lying on their sides to test whether the larger bias in angular direction in the

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[2] Studies of perceived direction in smaller scale spaces seem to show less evidence of this (e.g., Philbeck, Sargent, Arthur & Dopkins, 2008; see also Fortenbaugh, Sanghvi, Silver, & Robertson, 2012). See Li & Durgin (submitted) for a review of these findings.

vertical axis is yoked to the body's sagittal axis (in which case it would be smaller when on one's side) or to the world-relative vertical axis.

Experiment 1. Perceived 45° elevation direction in tilted observers

To initially test whether the angular biases in perceived direction are world-referenced (allocentric) or body-referenced (egocentric), we conducted two procedures in Experiment 1. The first involved height-distance matching, such as shown in Figure 1, but with observers in various states of body orientation. This task served as an implicit measure of perceived angular direction in elevation (Li et al., 2011). The second procedure involved explicit production of a 45° direction in elevation above the horizon (the direction halfway between horizontal and vertical), again with observers in various states of body orientation.

Method

Participants. Ninety-six undergraduates (54 female) from Swarthmore College participated in this brief experiment in exchange for payment. All participants had normal or corrected to normal vision. Observers were randomly divided among four viewing conditions (24 per condition). This is a sufficient sample size to have power of 90% for detecting a 5° difference from the 30° expected value in each condition assuming a standard deviation of 7° (Durgin & Li, 2011; Li et al., 2011).

Apparatus and Tasks. The main apparatus was a moveable cart (Figure 2) that could support an observer at normal eye-height while tilted sideways at 45°, lying on their side at 90°, or sitting upright. In a fourth condition, participants stood and walked, but in the three other conditions they were transported on the cart. Eye height in all three of the cart conditions was about 1.6 m. In the height-distance matching task, the experimenter rolled the cart forward or back at the participants' instructions (or the participant walked) until the participant felt that they were the same distance from a (10 m tall) lamp post as the post was tall. In the explicit angular direction (or angle bisection) task participants were to similarly adjust their position (e.g., by walking or by instructing the experimenter which way to move them) until they felt that they were looking up at a 45° direction at the top of a column holding a water tank (the column was 35 m tall). It was explained that the 45° was defined relative to true horizontal (rather than the slanted ground) and that they were therefore to position themselves so as to be looking up in a direction which bisected the angle between horizontal and vertical.

Line drawings were used to illustrate the intended positioning and visual target for each of the tasks. The drawings from the cart conditions and the two stimuli are shown in Figure 3. Note that the terrain leading up to the water tower was slanted[3], which served, in combination with the explicit instructions, to discourage attempts to solve the explicit angular direction task by using height-distance matching (see also Durgin & Li, 2011, Experiment 1).

Design. Each participant performed just one trial of each of the two tasks (height-distance matching task and explicit angular direction task) in one of the four viewing conditions (Sitting upright, Tilted 45° to the left, lying Sideways, or Walking upright). The height-distance matching task was always performed first (to preserve its status as an implicit measure of visual direction). *Initial location* (*Far* or *Near*) was varied between subjects and within subjects to control for possible anchoring effects (Shaffer, McManama, Swank, Williams & Durgin, 2014). Participants who were started from the Near initial location for the distance to height matching task, were started from the Far initial location for the angle production task and vice versa. The Near and Far initial locations were 5 m and 20 m for the distance matching task and 17.5 m (59°) or 70 m (27.5°) for the direction bisection task.

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[3] The ground slant in the approach to the water tower was variable but was always slanted down away from the tower. It changed fairly smoothly from nearly flat near the tower, to 3° at about 30 m from the tower and then to 5° at the entrance to the parking area (about 40 m from the tower); it was consistently 3° beyond 50 m. In contrast the approach to the lamp post was nearly flat (and sloped less than 1.5° over any given 1 m distance throughout).

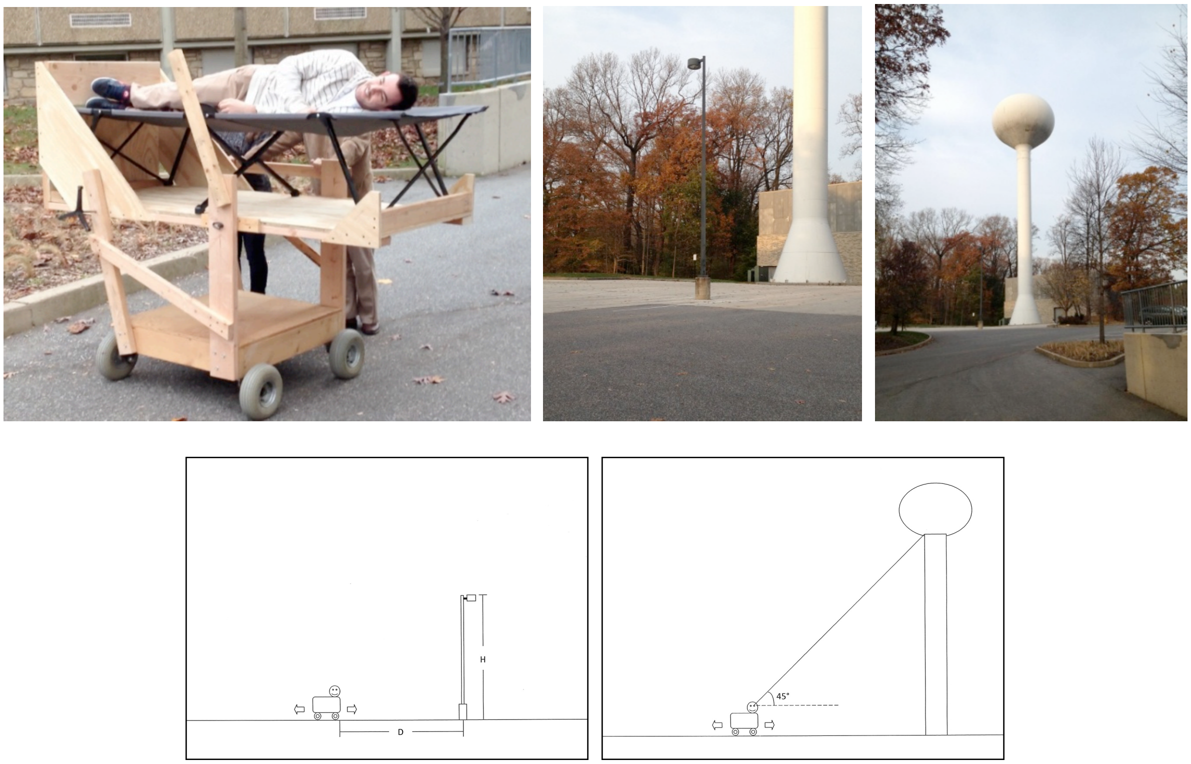

Figure 3. Cart (top left) and light pole (top middle) and water tower (top right) used in Experiment 1; images used when instructing participants for the height-distance matching task (bottom left) and explicit angular direction task (bottom right). The cart platform could be raised up for a sideways observer (as shown), lowered down (for a seated observer) or tilted at 45°, by lowering only the foot-supporting end of the platform.

Procedure. Participants were led or transported to the initial location with eyes closed. Once in position, they were allowed to open their eyes and were instructed with the help of a diagram indicating the goal of the matching task (Figure 3, lower left). Once they understood the task, the trial began. They walked or directed the experimenters to move the cart until they felt their distance from the lamp post matched the height of the lamp post. Their distance from the lamp post was then measured with a laser range finder.

Participants were then asked to close their eyes again and were led or transported to the initial location for the explicit angular direction task. Once in position, they were again allowed to open their eyes and were instructed with the help of a diagram showing an overview of the explicit angular direction task (Figure 3, lower right). It was pointed out to them that they should not match distance and height (because the ground was not level), but should perform this task based on the perceived elevation direction of the line of sight to the top of the supporting column for the water tower as shown in the diagram. Once they understood the task, the trial began. The distance between the final stopping location and the water tower was measured with the laser range finder. These distances were later converted to angles based on an interpolated function using direct measures of visual direction to the top of the water tower column (using a sighted inclinometer) from eye-height at regular intervals along the (variably slanted) path of translation.

Results

Although explicitly perceived angular direction was measured second (so as not to contaminate the height-distance matching task) we report the analysis of the explicit angular direction task first.

Explicit angular direction. If angular expansion in the vertical axis were tied to body orientation, we would expect sideways participants to exaggerate vertical angles less than upright participants and therefore position themselves closer to the water tower than upright participants. A 4 (*Orientation*: Walking, Sitting, Tilted, or Sideways) x 2 (*Initial location*: Near or Far) factor ANOVA conducted with the direction data found no reliable effect of bodily *Orientation*, $F(3, 88) = 1.08$, $p > .250$, $ges = 0.04$; nor any interaction between *Orientation* and *Initial location*, $F(3, 88) = 1.11$, $p > .250$, $ges = 0.04$. There was a reliable anchoring effect caused by *Initial location*, $F(1, 88) = 188.2$, $p < .001$, $ges = 0.68$, implying that participants made insufficient adjustments from the initial locations. To better represent the central tendency of the adjustments, the anchoring effect was modeled as a fixed proportion of adjustment within each orientation group, and individual settings were compensated accordingly. Figure 4 shows that the mean perceived 45° was about 30° from horizontal in all four orientations, consistent with perceptual angular expansion by 1.5. That is people thought they were looking up at a 45° angle when their actual gaze direction was only 30.7° above horizontal, 95% CI [29.2°, 32.1°].

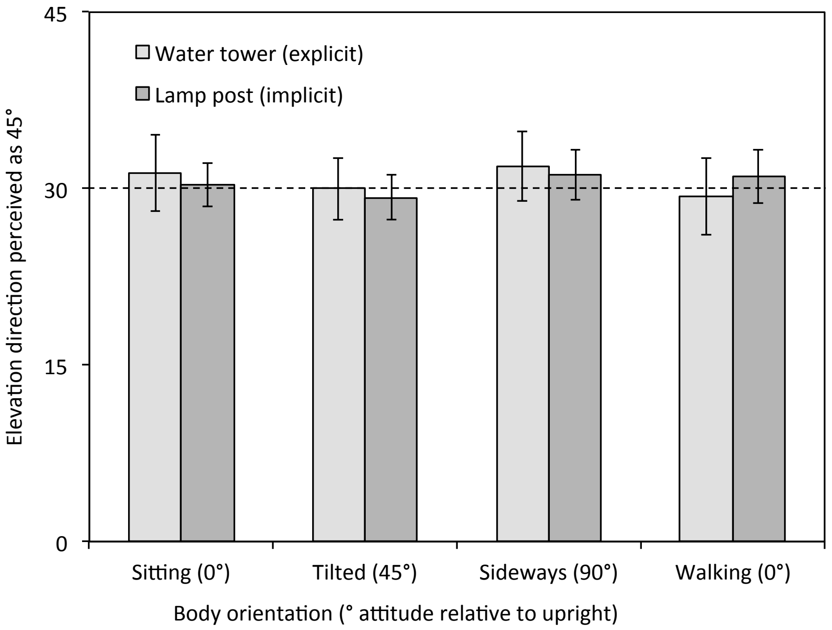

Figure 4. Optical direction in elevation from horizontal perceived as 45° (estimated match point) in both tasks of Experiment 1. Dashed line represents predictions based on an angular gain of 1.5 (*Angular Expansion Hypothesis*). Bars show 95% CIs for each viewing condition and task.

Height-distance matching. A similar repeated measures ANOVA on the height-distance matching data for the lamp post found no evidence for an effect of body *Orientation*, *F*(3, 88) = 1.19, *p* > .250, *ges* = 0.04, nor any evidence of an interaction between *Orientation* and *Initial location*, *F*(3, 88) = 1.44, *p* = .236, *ges* = 0.05. There was again a reliable anchoring effect caused by *Initial location*, *F*(1, 88) = 54.9, *p* < .001, *ges* = 0.38, so the same proportional compensation method was applied to this adjustment data. The resulting match points for distance (M = 14.7 m; 95% CI [14.1, 15.2], for the 10 m lamp post) were converted to angular values equivalent to those recorded in the explicit angle task (i.e., the optical direction from eye-level to the top of the lamp post), on the assumption that participants neglected their eye-height for such a tall pole and sought the 45° even for the height-distance matching task. The mean resulting angles, also shown in Figure 4, are consistent with the 30° estimate computed from the explicit 45° angular production data. The overall mean angle was 30.4°, 95% CI [29.5°, 31.4°].

Discussion

Even with observers who lay on their sides, perceived matches between height and distance (an implicit measure of the perceived 45° elevation) and explicit productions of the perceived 45° elevation direction both indicated values (~30°) consistent with the previously measured gain of 1.5 for perceived deviations in elevation from horizontal (Durgin, 2014; Durgin & Li, 2011). It thus appears that perceived directional distortions in locomotor space are tied to the external reference frame. A limitation of this experiment was that we did not measure perceived direction in azimuth. In Experiment 2, we address this by considering whether large asymmetries in the perception of horizontal and vertical extents in locomotor space are similarly tied to the world reference frame and whether they are quantitatively consistent with differential angular expansion in perceived azimuth and angular elevation.

Experiment 2. The large-scale asymmetry between horizontal and vertical

It is well known that vertical lines appear slightly longer than horizontal lines (Fick, 1895). The magnitude of this illusion when measured with lines is typically 4-6% (Avery & Day, 1969; Finger & Spelt, 1947; Prinzmetal & Gettleman, 1993; but see Armstrong & Marks, 1997). However, much greater overestimation of vertical extents relative to horizontal extents has been reported for large outdoor objects (Chapanis & Mankin, 1967; Dixon & Proffitt, 2002; Higashiyama, 1996; Higashiyama & Ueyama, 1988; Yang, Dixon, & Proffitt, 1999). The magnitude of the outdoor version of the illusion has been reported to be as high as 25% for large objects. We hypothesized that the magnitude of the large-scale object illusion may correspond to the quantitative difference between angular expansion gains measured for left/right (azimuthal) direction (1.2-1.3; Foley et al., 2004; Li & Durgin, submitted; Li et al., 2013) and for up/down (elevation) direction (1.5; Durgin & Li, 2011).

The normal (small-scale) horizontal-vertical illusion (HVI) is thought to be retinotopic, such that sideways observers see physically horizontal lines as longer (Avery & Day, 1969; Künnapas, 1958), whereas the angular exaggeration of vertical angles was not reduced when observers were rotated in Experiment 1. If the large-scale HVI is primarily due to differential angular exaggerations of perceived allocentric direction (perhaps with an additional contribution from the retinotopic HVI), we would expect that the large asymmetry in perceived size for large horizontal and frontal extents would be mainly preserved for sideways observers of large-scale scenes.

We note that Higashiyama (1996) conducted related experiments with sideways observers, but did not have them directly compare horizontal and vertical extents. Rather, each compared vertical and horizontal frontal extents on the face of a building to depth extents. Higashiyama reported fairly small differences between distance matches to horizontal and vertical extents when observers were on their sides, but his cart was only 0.32 m high and this may have reduced the utility of using the ground plane in conjunction with perceived angular declination because this unusually close proximity to the ground plane would have dramatically altered the relationship between declination and distance. In the present experiment we maintained approximately the same eye-height for rotated observers (1.6 m) as for upright observers, and we had them directly match vertical objects with frontal horizontal ground extents.

Method

Participants. Forty-eight undergraduates (31 female) from Swarthmore College participated in Experiment 2 for payment, so that we would again have 24 per orientation condition. This allowed for 95% power for detecting a 4% difference between orientations assuming a standard deviation of 5% (Yang et al., 1999). All participants had normal or corrected to normal vision.

Design. Body *Orientation* (standing *Upright* or lying *Sideways*) and *Ocularity* (*Monocular* or *Binocular*) were manipulated as between-subject variables, with 12 participants randomly assigned to each combination. Ocularity was manipulated because the small-scale HVI is thought to be influenced by this (Prinzmetal & Gettleman, 1993). Five *pole heights* (3, 4.5, 6, 7.5 and 9 m) were tested at two *initial* *frontal distances* (short or long) for each participant with random variation in the short and long positions. The participants' task was to position the experimenter, who was holding a short pole (1.2 m) and standing to the left side of the tall pole, so that the distance between the tall pole and the short pole matched the height of the tall pole. (Yang et al., 1999, showed that the comparison of a horizontal gap and a vertical extent was not itself sufficient to produce a large-scale HVI.) The order of the 10 combinations of *Pole Height* and *Initial Distance* was randomized.

Figure 5. Photograph of the experimental setup in Experiment 2. The participant (left) either lay sideways on the wooden cart (as shown) or stood in the same location. Their task was to direct the experimenter (holding a short pole) to move left or right until the perceived distance between the tall pole and the short pole matched the perceived height of the tall pole.

Apparatus. The experimental set-up is shown in Figure 5. The cart used in Experiment 1 was used to support sideways observers in a stationary position during the experiment. The viewing position was 15 m back and approximately 1.6 m (i.e., a typical eye-height) to the left of and above the base of the stationary vertical pole position. Upright participants stood in the same viewing location. The five poles, constructed from aluminum alloy downspout material, were stored out of sight in a drainage ditch at the back of the field, which was not visible from the viewing location. They were mounted prior to each trial on a heavy metal bracket by the experimenter while the participants' eyes were closed. Participants in the monocular conditions wore an eye-patch on one eye. A laser range-finder was used to measure the final distance between the tall pole and the short pole.

Procedure. Once participants had consented to the procedure and were ready (e.g., on the cart or standing, with an eye patch or not, as required), they were instructed with the help of a diagram showing an overview of the task. Once they understood the task, the judgments began. They directed the experimenter to move until they felt the distance between the two poles appeared the same as the height of the tall pole. The actual distance was then recorded with a laser range finder. The participants were asked to close eyes between trials while the experimenter prepared the next trial. Only one of the tall poles was visible in each trial.

Results

The mean perceived height-to-width ratio (i.e., matched width-to-height ratio) is plotted as a function of height and body orientation in Figure 6 (left). An ANOVA with 2 between-subject factors (*ocularity* and *orientation*) and 2 within-subject factors (*pole height* and *initial frontal distance*) was conducted with the ratio data. A reliable effect of *body orientation* was found such that the perceived height-to-width ratio was larger in the upright observers, $F(1, 44) = 9.57$, $p = .003$, $ges = 0.119$. There was also a reliable effect of *pole height*, $F(4, 176) = 14.87$, $p < .001$, $ges = 0.057$, and a reliable (anchoring) effect of *initial frontal distance*, $F(1, 44) = 26.78$, $p < .001$, $ges = 0.028$. The mean anchoring effect was 3.1%, 95% CI [2.0%, 4.2%]. The effect of *ocularity* was not reliable, $F(1, 44) = 1.00$, $p > .250$, $ges = 0.014$, nor was there an interaction between *ocularity* and *orientation*, $F(1, 44) < 1$, $p > .250$, $ges < 0.001$. It can be seen from Figure 6 that perceived height-to-width ratio in both upright and sideways observers increased with the *pole height*, which is consistent with Yang et al.'s (1999) observation. A sideways body orientation reduced the magnitude of the outdoor HVI but did not reverse it.

The reduction in the sideways condition comports with the idea that there may be two components in outdoor HVIs: An egocentric component (traditional HVI) and an allocentric component (caused by the angular elevation bias being larger than the azimuth bias). The implied magnitudes of the allocentric and egocentric components are shown in Figure 6 (right) as a function of pole height. The allocentric component is computed as the geometric mean of the two ratio values; the egocentric component is the square root of the ratio between them[4]. The allocentric component increased with the pole height, reaching 20% for the taller poles with an overall mean value of 16%, 95% CI [10%, 21%], and a mean value of 19% for the 3 tallest poles, 95% CI [16%, 21%]. This closely corresponds to the 20% effect predicted by prior estimates of the ratio between bias in azimuth and elevation angular expansion. In contrast, the egocentric component had a fairly constant magnitude across pole heights with a mean value of 5.4%, 95% CI [3.9%, 6.9%]. This closely corresponds to prior estimates of the retinotopic HVI.

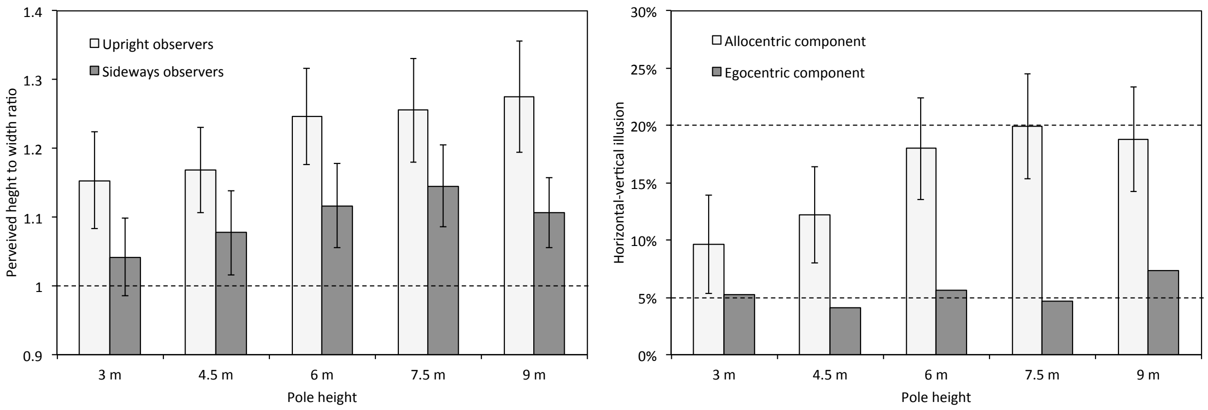

Figure 6. Results of Experiment 2. Left: Mean perceived gravitational height-to-width ratio as a function of body orientation and of pole height. 95% CIs are shown. Right: The implied allocentric and egocentric components contributing to the outdoor horizontal vertical illusions at each pole height. (Dashed lines represent expected allocentric – 20% – and egocentric – 5% – contributions based on prior studies). CIs were computed for the

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[4] This way of modeling these component quantities assumes that the two components would be combined by multiplication or by division to obtain the observed ratios: Upright = Allocentric * Egocentric; Sideways = Allocentric/Egocentric. Thus Allocentric = (Upright*Sideways)$^{-2}$ and Egocentric = (Upright / Sideways)$^{-2}$.

allocentric component by calculating the implied allocentric contribution for each observer assuming a 5% retinotopic HVI.

Discussion

The large-scale HVI appears to be composed of at least two components (see also Williams & Enns, 1996, who demonstrated independent contributions of pictorial depth cues and frame effects for the small-scale HVI): The smaller component is specific to the orientation of the observer, is about the size of the classic HVI, and is invariant with object size. For taller poles, the large allocentric component is quantitatively consistent with previously observed difference between the magnitudes of perceptual angular expansion in azimuth and elevation for the taller poles. The fact that the allocentric component is smaller for smaller poles may indicate a mixed strategy where another source of information (i.e., in addition to visual direction) plays some role in the comparison of the smaller objects (Yang et al., 1999). For example, the evaluation of shape differs from the evaluation of distance (Loomis et al., 2002) and large-scale size. In addition, the large asymmetric directional distortions that seem sufficient to explain the large-scale HVI apparently don't affect smaller scale scenes (Dixon & Proffitt, 2003).

The present experiment provides support for the notion that the allocentric component of the large-scale HVI may be based in the angular directional distortions of the angular expansion hypothesis given that Experiment 1 showed that these are also allocentric. This is because the magnitude of the allocentric component for the three larger poles (i.e., 1.2 or ~20%) is quantitatively consistent with prior estimates of the difference in gain between the angular expansion gain for perceived elevation (1.5; Durgin & Li, 2011) and the angular expansion gain for perceived azimuth measured when the retinotopic HVI is taken into account (1.25; Li & Durgin, submitted). That is, 1.5 divided by 1.25 equals 1.2, which predicts a 20% overestimation of height compared to width.

A direct comparison with the results of Higashiyama (1996) is complicated by several methodological differences, but Higashiyama concluded that mismatches between body orientation and visual orientation (when observers were on their sides) resulted in substantially weakened illusions (e.g., 4%) whereas ours averaged 10%. On our account, the largest sources of bias (the ground plane reference frame) may have been somewhat compromised for sideways observers in Higashiyama's study because, in addition to lying on their sides, they were low to the ground and were looking at the face of a building. It may be quite important that in our study the observers were at normal eye-height and that the horizontal extent was a ground interval rather than an interval on the face of a building.

Experiment 3. Is the ground plane sufficient?

In order to dissociate the effects of a visual ground plane from the effect of gravity *per se* we tested a new set of participants using an immersive virtual environment in which the visual scene was reoriented by 90°. Reorienting the visual world rather than the observers dissociates the ground-plane from most other sources of bias including gravity, retinotopic biases, and any bias provided by the field of view of our head-mounted display (HMD). If the visual reference frame defined by the seen ground plane is the basis for the asymmetric distortion of space observed in Experiment 2, then the ground-based HVI component should remain approximately 20% in the present experiment. That is, objects protruding from a visual ground plane should show large ground-based HVI effects. If, however, the vestibularly-sensed direction of gravity determines the angular reference frame, then reorienting the scene by 90° should reverse the HVI, making "horizontal" extents along the ground plane (i.e., those along the vertical gravitational and body axis) appear larger than protrusions from the ground plane, and thus make the nominal HVI less than 1.0.

Method

Participants. Twenty undergraduates from Swarthmore College participated for payment in a between-subject design. All participants had normal or corrected to normal vision. The number selected was sufficient to detect a 5% difference in HVI between orientation conditions with 87% power, assuming a 5% standard deviation.

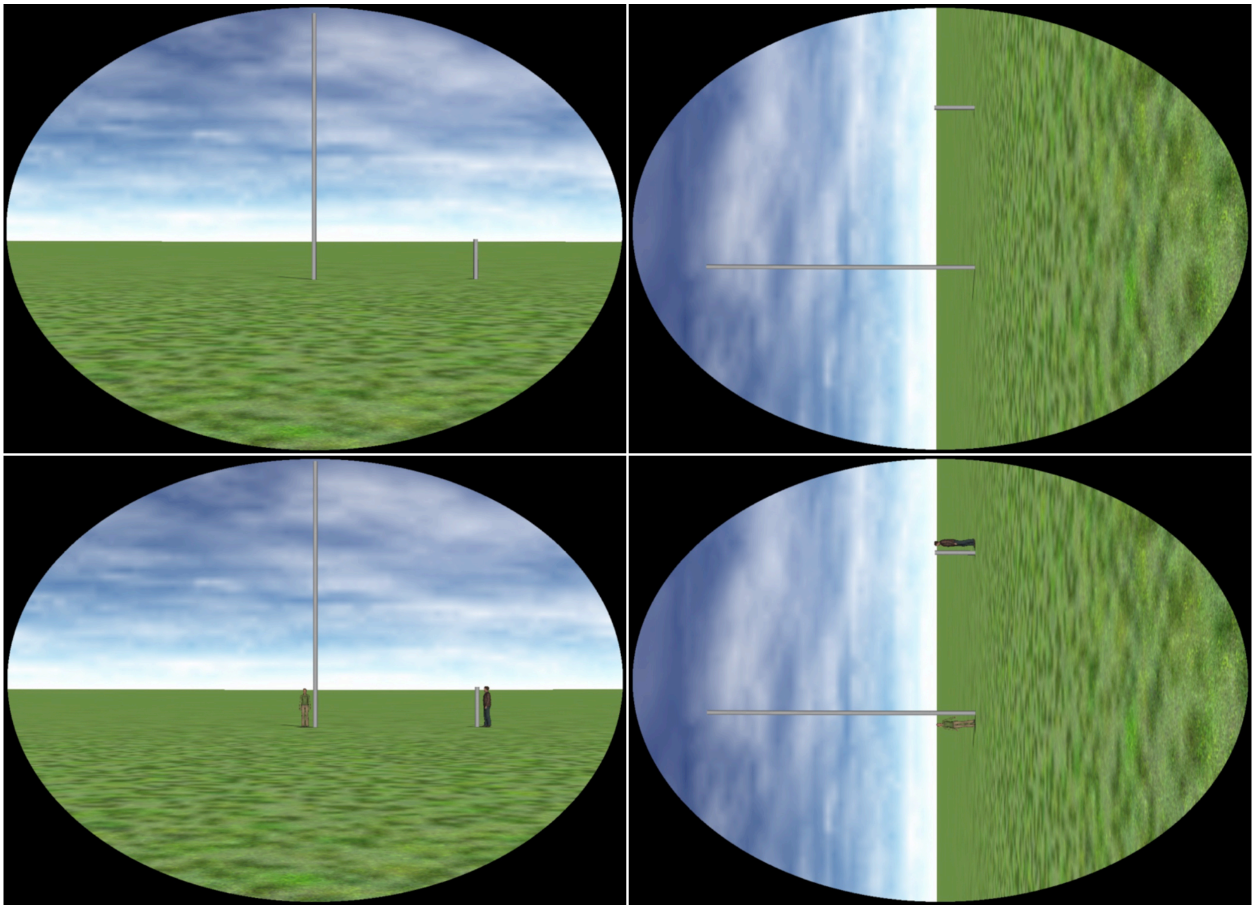

Figure 7. Screen-shots (cropped) of immersive stereoscopic displays from Experiment 3. At left, the basic scene consisted of a tall stationary pole and a shorter pole that could be moved along the ground to set the pole-to-pole horizontal distance. At right are shown a rotated world version of the same scene. Avatars were present (bottom row) near the poles for half the observers.

Apparatus and display. A zSight (Sensics Co.) HMD with 3D inertial updating was used so that participants could scan the scene. The binocular field of view of this HMD was verified to be 40° x 33°. The display resolution was SXGA: 1280 x 1024 pixels per eye. Eye-height and interpupillary distance were measured in advance. The displayed scene, which included stereoscopic depth information, was updated and rendered at 60 Hz, using Vizard 4.0 (Worldviz). The scene was viewed through a simulated aperture representing an oval window (39° x 28°) approximately 0.5 m in front of the observer, and yoked to the observer's head. An oval window was selected to avoid providing a visible 1:1 aspect ratio. The oval window was simulated as being in near space to remove cue conflict between the frame of the viewing window and the edges of the scene that it occludes. Because the oval window remained in the same orientation relative to the observer whether the world was sideways or upright, the oval frame would not contribute to the ground-based component of the HVI. That is, it might tend to produce additional bias in the same direction in the upright world condition, but in the opposite direction in the sideways world condition. Such frame effects have been demonstrated previously by Williams and Enns (1996).

The scene (shown in Figure 7) depicted a green ground texture rendered with high and low-spatial frequency noise patterns with the horizon set to eye level, a pair of gray poles (the tall pole and the moveable pole), and, for half the participants, avatars were shown standing on the ground plane to provide a stronger sense of the visual gravitational reference frame. (Including the avatars proved to have no discernable effect). A remote-control mouse was used by the participants to adjust the position of the adjustable pole (the nearer avatar walked along beside the pole when it was moved) and to move on to the next trial.

Design. Participants were assigned to one of four conditions crossing the manipulation of visual world orientation (Upright or Sideways) and the presence of avatars (Present or Absent). The pole heights used ranged from 3 to 24 m by increments of 3 m. The relatively small field of view meant that we had to present poles at a viewing distance 3 times their height to make them fully visible in the scene (as shown in Figure 7), but we also included nearer distance trials (distances of 1 and of 1.5 times the pole height) where head movements were required to scan the poles in order to increase immersion. Thus, we presented all 8 pole heights at distances of 1, 1.5, and 3 times their height. Initial frontal ground distances both larger and smaller than the pole height were used for each pole at each distance, so a total of 48 trials were performed, in random order, by each participant. Anchoring effects were accounted for prior to analysis by combining data from close and far anchoring trials using an anchor-proportional weighting for each pole height and viewing distance for each participant. This reduced the number of data points to 24 per participant. Our main interest was in estimating the ground-based component of the HVI. Although our design included pole height and relative viewing distance, our reports of component effects (based on a between-subject conditions) computed confidence intervals across the average matches to the eight pole heights (treating pole heights as items, and treating viewing distance as a nuisance variable; see the supplementary materials for more explanation) in each world orientation.

Procedure. At the beginning of the experiment, participants were instructed with the help of a diagram illustrating the matching task. Once it was clear that they understood the task, they signed a consent form, were fitted for the HMD, and started the trials. They used the radio mouse to move the short pole (the avatar walked with it when present) until the between-pole distance matched the height of the tall pole. Then they pressed a button to record the distance – which also triggered a new trial. A 1.5-sec blank screen was shown between trials.

Results and Discussion

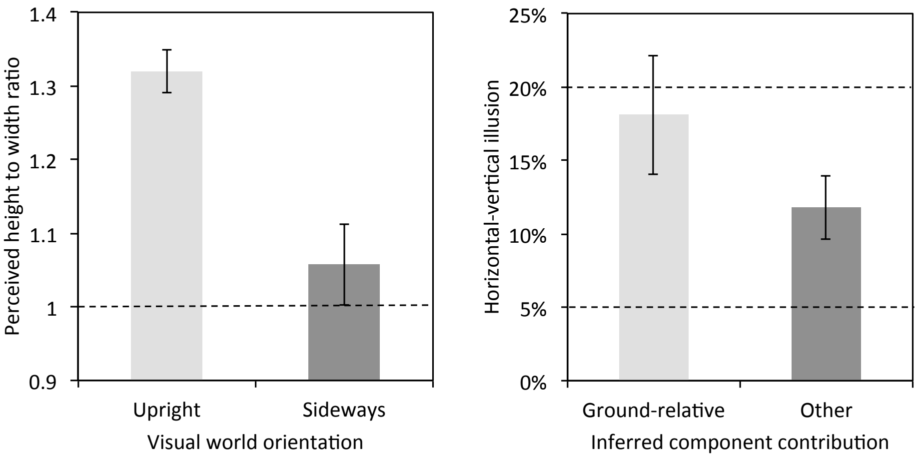

Figure 8. Results of Experiment 3. Left: The mean HVI ratio (i.e. the ratio between perceived pole height and perceived width with respect to the scene reference frame) for the upright and sideways scene orientation conditions. Right: the estimated

magnitudes of the ground-relative (allocentric) and other (non ground-based) components of the outdoor HVI with respect to the scene reference frame. Confidence intervals (95%) are shown.

An ANOVA with Visual World Orientation (Upright or Sideways) and Avatar Presence (Present or Not) as between-subject factors and Pole Height and relative Viewing Distance as within-subject factors was conducted with the ratio data. A reliable effect of Scene Orientation was found such that Sideways scene produced a smaller HVI (defined in scene coordinates), $F(1, 16) = 19.4$, $p < .001$, *ges* = 0.47; but no reliable effect of the Avatar Presence was found, $F(1, 16) = 1.28$, $p > .25$, *ges* = 0.05, nor was there an interaction between Visual World Orientation and Avatar Presence, $F(1, 16) = 0.26$, $p > .25$, *ges* = 0.01. As shown in Figure 8, the large-scale HVI remains attached to the ground plane even when the ground plane is dissociated from gravity.

Note that if there were no ground-based component, then the nominal HVI in the rotated world condition should have been reversed. That is, there should have been a retinotopic component, in any case, producing a (nominal) HVI that was *less* than one (since the HVI is defined in scene coordinates in Figure 8). Any gravitation-based effects or frame-based effects (Williams & Enns, 1996) should also have pushed the measured HVI less than 1. Thus, although the 95% confidence interval in the sideways world condition seems to include an HVI of 1.0, even an HVI of 1.0 requires that there be a ground-based component present in order to counter all the other likely sources of bias pushing the HVI below 1. This is because all the other sources of allocentric bias (all but the ground-based component) were aligned, in this experiment, with the retinotopic component.

Although there were also reliable effects of Pole Height, $F(1,16) = 17.8$, $p < .001$, *ges* = 0.08, and Viewing Distance $F(1,16) = 10.4$, $p = .005$, *ges* = 0.08 (see Supplementary Materials for details), these effect sizes were fairly small and the variables were not of primary theoretical interest. For example, the size effect appears to reflect a central tendency bias in the adjustment process, such that matches to shorter poles were relatively long and matches to taller poles were relatively short. This is certainly consistent with many other studies that show response compression effects (e.g., Li et al., 2103), but it is not of theoretical interest here. The effect of viewing distance is difficult to interpret because it is confounded with the need for head movements[5]. These could be of theoretical interest because head movements might, for example, make the gravitational framework more salient. However, the effect observed – that ground-based biases were reduced in the far viewing conditions – is inconsistent with such an effect, since this is the condition where head movements were not required. Moreover, even in the far viewing cases, the measured HVI in the sideways condition was greater than 1.0 for all but the tallest two pole heights (where response compression effects would have suppressed the effect).

Because the principal purpose of the experiment was to estimate the size of the ground-based allocentric component (by dissociating the ground-based contribution from all others), mean perceived height-width ratios for each of the 8 pole heights were used to estimate means and 95% confidence intervals for each world orientation: (Upright world: 1.32, [129, 1.35]; Sideways world: 1.06, [1.00, 1.11]). Similarly, ground-based and non-ground-based HVI components were calculated for each pole height and used to estimate means and 95% confidence intervals for these components (ground-based: 18%, [14%, 22%]; non-ground-based: 12%, [10%, 14%]). These are the data shown in Figure 8.

Overall, the magnitude of the ground-based HVI was quite similar in the present experiment to the allocentric component observed outdoors in Experiment 2. Thus, even with upright observers and the visual world tilted sideways, the evaluation of the extents of large-scale objects showed a substantial ground-based allocentric HVI component. The other (non-ground-based) portion of the HVI was much larger in the present experiment than in the outdoor experiment. It is very likely that this portion was enhanced by a contribution from the (allocentric) oval viewing aperture (Prinzmetal &

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[5] When the viewing distance was large so that the entire pole was visible at once, the magnitude of bias was reduced somewhat. This might be due to greater influence of a 2D shape strategy in the cases where the 2D shape was visible in a single fixation. More information is available in supplementary materials.

Gettleman, 1993; Williams & Enns, 1996), and it remains possible that it includes a contribution from the vestibularly-specified direction of gravity, though the present design does not afford further analysis of these other components. The main conclusion supported by the data, however, is that there is certainly a large, ground-based, allocentric HVI component, not reliably different in magnitude from the allocentric component observed in Experiment 2 (both include 20% in their confidence intervals).

General Discussion

In the present study we examined whether large asymmetric distortions in perceived direction in elevation and azimuth (i.e. Durgin & Li, 2011; Li & Durgin, submitted; Li et al., 2011, 2013) were tied to the allocentric reference frame of the ground plane. In Experiment 1 it was found that, for observers at eye-height, the perceived angle of elevation was exaggerated by a gain factor of 1.5 irrespective of the body orientation of the observer, which suggests that this directional exaggeration of perceived elevation is allocentric. In Experiment 2 we used the large-scale HVI as a probe, and found that quantitative predictions about the magnitude of the large-scale HVI could be derived from previously measured biases in perceived direction. The observed outdoor HVI in upright and sideways observers could be decomposed into an egocentric component (with a fixed magnitude of 5%) and an allocentric component (with a magnitude of about 20% for taller objects), which was replicated in a reoriented virtual environment in Experiment 3. These observations are consistent with the idea that the allocentric component in Experiment 2 was primarily ground-based as well. The calculated egocentric component in Experiment 2 was consistent with traditional HVIs observed in common laboratory settings (Avery & Day, 1969; Künnapas 1955), and the calculated allocentric component was quantitatively consistent with the asymmetry found in directional distortions (Durgin & Li, 2011; Higashiyama & Ueyama, 1988; Li et al., 2011).

The allocentric and ground-based components of the large-scale HVI measured in Experiments 2 and 3 may therefore reflect the biases present in the evaluation of direction for locomotor space as described in the *Angular Expansion Hypothesis* (AEH: Durgin & Li, 2011; Li & Durgin, 2012) and may be tied to the visually-defined ground plane (see Williams & Enns, 1996; but cf., Higashiyama, 1996). Asymmetric directional distortions can be used to quantitatively model downhill slope exaggeration (Li & Durgin, 2009), as well as a variety of ground-extent anisotropies (Durgin & Li, 2011, Foley et al., 2004; Li et al., 2011; Li et al., 2013; Li & Durgin, submitted). Thus, the present study used mathematical modeling based on non-verbal techniques of parameter estimation to extend the explanatory scope of the AEH to the large-scale HVI.

We have not primarily sought to contrast the AEH with other hypotheses in the present study (see Li & Durgin, 2012 for prior comparisons of the theory). Rather we sought to use parameter estimation to develop a further quantitative articulation of the hypothesis that could be applied to the large-scale HVI. It is important to mention, however, that several investigators have suggested that gravitational effort might contribute to the overestimation of vertical extents evident in hill perception (Kammann, 1967; Proffitt et al. 1995, Yang et al., 1999), and related ideas concerning sensitivity to danger have been proposed for perceived height (Jackson & Cormack, 2008; Stefanucci & Proffitt, 2009). The finding that the large outdoor HVI is allocentrically yoked to gravity is consistent with these gravitational scaling theories (but see Higashiyama, 1996). After all, even the evidence from Experiment 3 could be interpreted as reflecting the importance of the visual direction of gravity that is normally specified by a ground plane.

Though gravity is causally relevant to the importance of the visual ground plane, we would argue that a disadvantage of gravitational scaling theories is that they typically only make signed predictions, and thus depend primarily on null hypothesis testing. But if hill slant exaggeration is due to behavioral potential, why are farther hills judged to be steeper (Bridgman & Hoover, 2008)? Similiarly, if hill slant exaggeration is affected by danger, why do steep downhills seem shallower when one stands closer to the edge (Li & Durgin, 2009)? These two effects have been quantitatively modeled in the process of developing the AEH using parameter estimation (Li & Durgin, 2009, 2010): Logarithmic effects of viewing distance on slant (likely related to increasing limits on binocular information processing with distance) are additive with systematic slant exaggeration at each viewing distance. This AEH model of slant (Li & Durgin, 2010; 2013), with no free parameters, can accommodate both hill data (e.g., Proffitt et al., 1995) and data concerning slant perception at near viewing distances (e.g., Durgin, Li & Hajnal, 2010).

The notion that perceived space has an allocentric affine geometry (e.g., Wagner, 2006), in which the various axes of space are scaled differently than one another might also be said to be consistent with the allocentric component of the large-scale HVI. On this account, the vertical axis (which is also normally the gravitationally relevant axis) is simply scaled differently than the frontal horizontal axis and both are scaled differently than the horizontal depth axis. Such a summary provides an equally concise description of the present results as the AEH. Indeed the AEH might be regarded as a specific variant of a non-Euclidean approach that includes a functionalist theoretical justification. Consider that Foley et al.'s (2004) non-Euclidean solution to the mapping of exocentric distances on the ground plane appealed to an azimuthal angular expansion as the best model of the layout of the ground plane. In this sense, our work on the AEH is an extension of the non-Euclidean tradition to the vertical axis, using a formulation involving angular expansion in perceived angular elevation/declination.

However, there are good reasons for believing that many of these effects might be due primarily to angular expansion effects rather than axis compression effects. For one, our initial parameter estimates of angular bias (Durgin & Li, 2011; Li & Durgin, 2009) involved independent measurement of biases in perceived angular direction in cases where the observed objects were not on the ground plane (e.g., to virtual objects suspended in space; Durgin & Li, 2011, Experiment 4), or were on a slanted ground plane (e.g., Durgin & Li, 2011, Experiment 1). In such circumstances, the comparison of horizontal distance and vertical height as a means of estimating angular direction is discouraged by the absence of visible surfaces to measure along those axes, yet the angular expansion parameters we measured (a gain of 1.5 for estimated elevation angles) are consistent with the angular parameters used in later applications of the AEH to biases in perceived ground distance (e.g., Li, Phillips & Durgin, 2011), including the present one. Moreover, estimates of perceived slant when looking up or down at sloped surfaces can be used to infer perceived gaze direction based on assuming a common perceived optical slant function (perceived slant relative to the direction of gaze). Data from two different experiments using this technique both imply the same angular expansion parameter (i.e., 1.5) for perceived direction of gaze (Durgin & Li, 2011, Experiment 4; Li & Durgin, 2009) to account for perceived surface orientation (see also Li & Durgin, 2010). This kind of converging evidence seems much more difficult to account for using an affine compression model. Finally, the use of numeric angular estimates is justified by stability in those scales (e.g., Durgin et al., 2010) and by comparisons between implicit measures of perceived orientation and explicit numeric estimates (Li & Durgin, 2010). In sum, although there may be additional affine distortions produced by other sources of information about distance, such as the mis-scaling of stereoscopic depth information (e.g., Johnston, 1991; Li & Durgin, 2013), the angular expansion account of bias in estimates of ground extents is quite parsimonious because it can quantitatively account for such a wide variety of systematic spatial biases. Appealing to the functionally-useful dense coding of angular direction, it provides a functional explanation for the long-observed underestimation of ground distance, for example. This is particularly relevant given that angular declination is known to be a powerful source of ground distance information even in the absence of binocular information (e.g., Wallach & O'Leary, 1982).

Because the AEH is a functional/informational account, the yoking of the AEH to the ground plane should not be surprising. The ground plane is known to be a very important source of information about spatial layout (Meng & Sedgwick, 2007; Ooi & He, 2007). Indeed, many studies seeking to measure non-Euclidean metrics of space intentionally obscure the ground plane as a confounding source of information (e.g., Koenderink, Van Doorn & Lappin, 2000; Todd et al., 2001; but see Foley et al., 2004; Norman et al., 2005). Conversely, it seems likely that the AEH is primarily relevant when a ground plane is present, and that it thus represents an informational structure that applies to a subset of spatial tasks (Li & Durgin, 2012; Loomis et al., 2002).

Why should there be an asymmetry between expanded perception of orientation in elevation and azimuth? Greater expansion in elevation can be motivated by two considerations: angular range and ground compression. First, the range of viewing directions relevant for evaluating ground distance, for example, is much smaller in elevation. Looking below 45° (two steps ahead), for example, is quite rare during locomotion (Marigold & Patla, 2006). Moreover ground distances become essentially frontal to gaze when gaze is lowered beyond this. In contrast the range of angles observed in azimuth during forward gaze is much larger, and so there is less room for expansion. Second, the elevation axis can serve as a measure of egocentric ground distance. Azimuth does not. Angular expansion in the elevation axis “uncompresses” angular measures of the ground. In contrast, frontal ground extents (for which azimuth is relevant) are usually compressed only by viewing distance rather than by the incident angle of gaze itself. Indeed, using an aspect ratio task comparing frontal and depth extents along surfaces, Li and Durgin (2013) observed equivalent angular expansion in perceived optical slant for surfaces slanted in pitch or in yaw – once the retinotopic HVI (measured for each observer) was taken into account.

And why should action control, which is often thought of as egocentric, benefit from an allocentric reference frame? Actions in locomotor space (e.g., walking, throwing) must be controlled with respect to the ground but also with respect to gravity. The visual ground plane may often serve as a surrogate for gravity – though normally not without contributions from vestibular information that may help to detect ground tilt (Gibson & Mowrer, 1938). Moreover, the head can tilt and swivel independent of the body itself. In these cases the perceptual orientation constancy that is normally maintained provides the basis for bodily actions that are affected by gravity – such as walking and throwing. Under most (i.e., upright) circumstances, counting on the verticality of the body and yoking one's actions to an allocentric visual reference frame may be the most adaptive approach.

The AEH is an information-based theory that suggests that systematic spatial bias (due to dense coding of angular variables) may serve the informational goals appropriate for the more sensitive control of action. It is proposed that this information is dense coded with respect to the reference frame of the ground plane despite resulting in large-scale distortions of perceived direction, slant, and extent. The present data indicate that these large-scale distortions in the perception of locomotor space are not yoked to the sagittal plane of the body. Rather, they appear to be tied to the allocentric reference frame defined by the horizontal ground plane on which the majority of our large-scale actions take place.

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Supplementary materials: Data from Experiment 3

The use of a virtual environment in Experiment 3 allowed us to dissociate visual world orientation and physical gravity, but forced us to choose how to handle the fairly limited field of view available in our immersive virtual environment. We believe any set of choices would likely produce measurement artifacts. For example, there was a fairly systematic effect of pole height on the produced ratios. However, as shown in Figure S1, this was most pronounced for the near viewing distances (1 and 1.5 times the pole height), which required visual scanning to see the entire pole. The systematic effect of pole height may therefore have been due to range effects or regression to the mean in memory (i.e., the short term memory in which pole height was stored while the gap between poles was adjusted), and thus we treated pole height simply as a source of variance in the main paper given that these kinds of range effects can be thought of a reflection of uncertainty (see Li et al., 2013, Experiment 3).

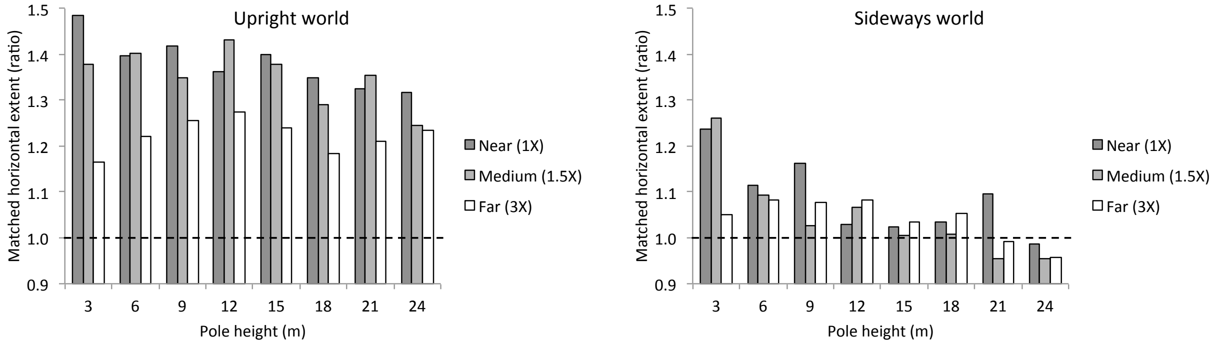

Figure S1. Complete average data for Experiment 3, showing the mean ratio setting for each pole height and each pole distance both for the upright visual world conditions (left) and for the sideways visual world conditions (right).

Conversely, there was also an effect of (proportional) viewing distance that suggests that when people saw the entire pole within the viewing aperture (as illustrated in Figure 7 in the main text), they may have tended to default to a 2D (e.g., shape) comparison of the extents, resulting in a smaller HVI.

Because the distance effect was hard to interpret with any confidence, however, we simply collapsed across the three viewing distances in Figure 8 in the main text.

In summary, we concluded that interpreting the systematic effects of pole height and of viewing distance as anything other than sources of variance or experimental artifact was inadvisable for this study. Both effects may be artifacts of the use of repeated measures or of virtual environments. Neither variable was of particular theoretical significance for the present experimental goals.

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