Perceived azimuth direction is exaggerated: Converging evidence from explicit and implicit measures

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Recent observations suggest that perceived visual direction in the sagittal plane (angular direction in elevation, both upward and downward from eye level) is exaggerated. Foley, Ribeiro-Filho, and Da Silva's (2004) study of perceived size of exocentric ground extent implies that perceived angular direction in azimuth may also be exaggerated. In the present study, we directly examined whether perceived azimuth direction is overestimated. In Experiment 1, numeric estimates of azimuth direction (−48° to 48° relative to straight ahead) were obtained. The results showed a linear exaggeration in perceived azimuth direction with a gain of about 1.26. In Experiment 2, a perceptual extent-matching task served as an implicit measure of perceived azimuth direction. Participants matched an egocentric distance in one direction to a frontal extent in nearly the opposite direction. The angular biases implied by the matching data well replicated Foley et al.'s finding and were also fairly consistent with the azimuth bias function found in Experiment 1, although a slight overall shift was observed between the results of the two experiments. Experiment 3, in which half the observers were tilted sideways while making frontal/depth extent comparisons, suggested that the discrepancy between the results of Experiment 1 and 2 can partially be explained by a retinal horizontal vertical illusion affecting distance estimation tasks. Overall the present study provides converging evidence to suggest that the perception of azimuth direction is overestimated.

Introduction

The geometrical structure of space is not always perceived veridically, even under full-cue viewing conditions. For example, it has been well documented that distance along a sagittal plane (in-depth distance) is perceptually foreshortened relative to distance along frontal parallel planes (frontal extent). This is known as distance anisotropy (Beusmans 1998; Foley, Ribeiro-Filho, & Da Silva, 2004; Levin & Haber, 1993; Li & Durgin, 2010, 2013; Li, Phillips, & Durgin, 2011; Li, Sun, Strawser, Spiegel, Klein, & Durgin, 2013; Loomis, Da Silva, Fujita, & Fukusima, 1992; Loomis & Philbeck, 1999; Loomis, Philbeck, & Zahorik, 2002; Toye, 1986; Wagner, 1985). Whereas this spatial bias in distance perception has been mostly studied in the context of research on the geometry of visual space (e.g., Foley et al., 2004; Gilinsky, 1951; Levin & Haber, 1993; Toye, 1986; Wagner, 1985; for an excellent review on the geometry of visual space, see Wagner, 2006), it has also provided evidence of perceptual biases in angular variables.

For example, in studies of anisotropy in perceived exocentric extent (distance between two targets on the ground), a common finding is that the magnitude of the anisotropy increases with viewing distance (e.g., Kudoh, 2005; Li & Durgin, 2010, 2013; Loomis et al., 1992). Whereas the increased bias with distance is consistent with an affine model of visual space (Li & Durgin, 2013; Wagner, 1985), it is also in line with the assumption that the distance anisotropy is primarily a result of misperception of optical slant—surface orientation relative to the line of sight (Li & Durgin, 2010, 2012a, 2013). That is, by the principles of shape and size constancy, when an exocentric in-depth ground extent is viewed from a distance, its size can be estimated by its visual angle, the viewing distance, and the optical slant (see Figure 1). Therefore, overestimation in perceived slant, which is itself distance-

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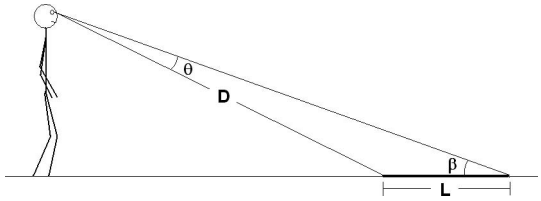

Figure 1. Exocentric in-depth distance, *L*, can be estimated using the visual angle subtended, θ, the viewing distance, *D*, and the optical slant, β. That is, according to the law of Sines, (sin θ)/*L* = (sin β)/*D*. Thus, $L = D \sin\theta/\sin\beta$. Overestimation in perceived β would result in underestimation in perceived L.

dependent (Li & Durgin, 2010, 2013), could be partly responsible for the anisotropy in exocentric distance perception. Direct support for the slant account comes from the findings of Loomis and Philbeck (1999). By elevating their observers, Loomis and Philbeck showed that when optical slant was kept constant, perceived aspect ratio under monocular viewing became nearly invariant to viewing distance. This result is consistent with the idea that the perceived aspect ratio was based on apparent optical slant information. Moreover, the data of Loomis and Philbeck suggested that the effect was not completely invariant with distance.

A smaller distance anisotropy has been observed when egocentric distance (i.e., the distance between observer and a target on the ground) is compared to a frontal extent (Li et al., 2011). The magnitude of this second anisotropy is nearly constant with viewing distances: Li et al. found that, for egocentric distances from 5 to 30 m, a physically matched frontal extent was perceived to be about 1.2 times of the egocentric distance. This anisotropy is smaller than the one found for relatively small exocentric extents, such as studied by Loomis and Philbeck (1999), where the matching ratio often exceeds 2:1. The crucial difference between these cases could be interpreted to be due to the difference between egocentric and exocentric extents. However, Li et al. (2013) found that the perceived ratio between frontal and in-depth extents was also about 1.2 for in-depth ground extents that were relatively large in visual angle. Li et al. (2013; see also Li & Durgin, 2012a) proposed that when an in-depth distance is angularly large (e.g., in the case of egocentric distance), its apparent length could be estimated by using visual direction in elevation to the two ends of the extent (rather than optical slant). It is already known that angular direction in elevation is a powerful source of information for the estimation of egocentric distance (e.g., Wallach & O'Leary, 1982; Williams & Durgin, 2015). This variable has been variously called "slope of regard" (Wallach & O'Leary), "angular declination" (Ooi, Wu, & He, 2001), and "gaze declination" (Durgin & Li, 2011a), but in the present paper we will refer to

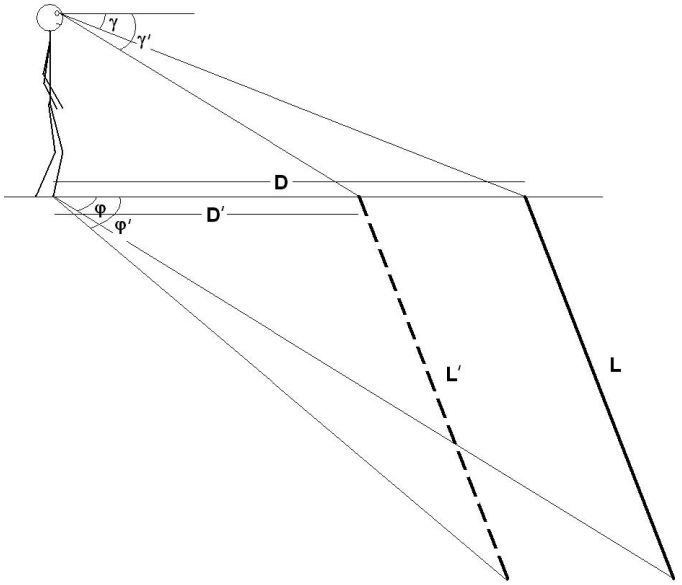

Figure 2. The perceptual anisotropy (Li et al., 2011) that makes frontal extent L appears larger ($L^{'}$) than the perceived egocentric distance, $D^{'}$, may be due to an exaggeration in perceived azimuth, $\varphi^{'}$. In fact, there is also evidence that perceived deviations in angular elevation, γ', are exaggerated relative to straight ahead in a manner that predicts egocentric distance underestimation, but if φ were perceived correctly, underestimation of egocentric distance would not cause anisotropy on its own. Note, this diagram is plotted in a perspective view. The extents *L*, $L^{'}$, *D*, and $D^{'}$ are all on a level ground plane.

the entire axis as *angular elevation* to correspond with our focus on azimuth[1] and use *angular declination* only when discussing exclusively the downward component of the angular elevation axis of space. Even if the underestimation of egocentric distance is explained in terms of bias in perceived direction of angular declination (Durgin & Li, 2011a), that angular bias alone is insufficient to explain the observation that frontal extents are perceptually longer than egocentric distances of equal physical size. As shown in Figure 2, misperception of the ratio between egocentric and frontal extents suggests instead that perceived azimuth direction must be overestimated.

It may seem counterintuitive to assume that perceived visual direction is distorted. How can we be wrong about our visual direction? However, how could one know that perceived visual direction is not systematically biased? It is often suggested that accurate action implies accurate perception. But actions can be calibrated to stably distorted perception, as shown in prism adaptation studies (e.g., Harris 1963; Held & Freedman, 1963). Just as people who wear glasses all day long do not normally notice the optical distortion introduced by the lens, we wouldn't be able

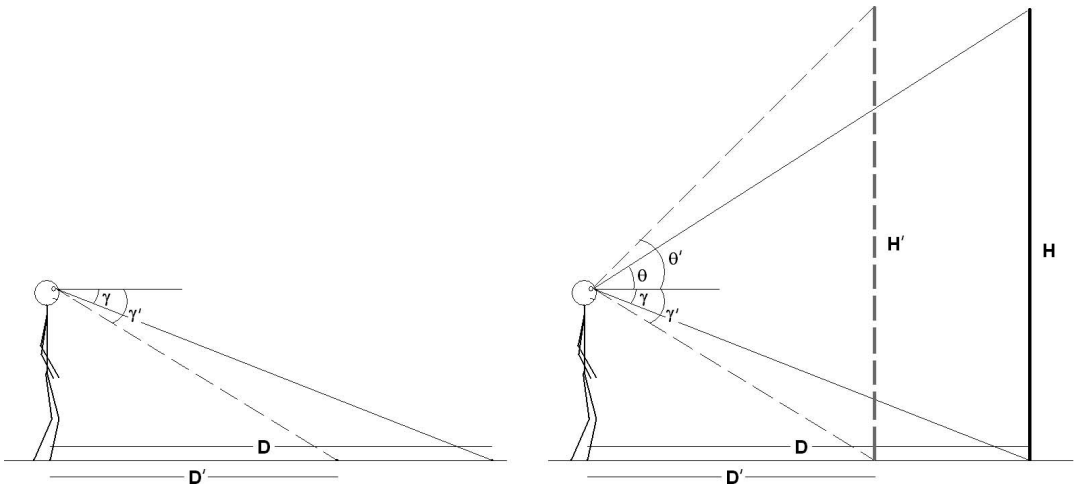

Figure 3. Diagrams suggesting that some perceptual biases in space perception can be well understood in terms of a distortion in perceived visual direction. Left: If the egocentric distance, *D*, is determined by angular elevation relative to straight ahead, γ, then perceptual exaggeration in perceived angular elevation, γ', should result in nearly linear compression in perceived egocentric distance, D′. Right: Under a similar logic, the distance-to-height ratio (D/H) will be perceptually distorted if both perceived visual direction below the horizon, γ', and perceived visual direction above the horizon, θ', are exaggerated.

to notice the stable distortions in perceived visual direction given that our perceived actions are coded in the same spatial framework as everything else.

A series of recent studies conducted in our lab suggest that perceived angular direction in elevation (i.e., visual direction in the sagittal plane) is distorted by a gain factor of about 1.5 (Durgin & Li, 2011a; Li, Phillips, & Durgin, 2011; Li et al., 2013). This distortion in perceived visual direction can quantitatively account for the linear compression (with a gain factor of about 0.7) in the verbal estimation of egocentric distance (e.g., as observed by Foley et al., 2004; see Figure 3 left; see also Loomis & Philbeck, 2008), and for the bias in the perceived distance-to-height ratio (e.g., Higashiyama & Ueyama, 1988; Li et al., 2011) illustrated in the right panel of Figure 3. Given the evidence that perceived visual direction in the sagittal plane is indeed expanded, it seems reasonable to test whether perceived azimuth direction may also be distorted.

In a study of the geometry of visual space, Foley et al. (2004) systematically measured the perceived size of egocentric and exocentric ground extents in a large grass field in natural viewing condition. Perceived sizes were assessed using numerical estimation. Substantial compression (with a gain factor of 0.7) was observed in perceived egocentric distance. More importantly, for the present purpose, exocentric extents with varied ground orientations relative to the line of sight of the observer were also examined. To account for their empirical data, Foley et al. proposed two mathematical models (one for perceived egocentric distance and the other for perceived exocentric distance). They found that to best fit their data with models, they had to assume that, when computing perceived exocentric distance, the visual angle signal has to undergo a magnifying transform. In other words, their study suggested that perceived azimuth angle might be overestimated. However, perhaps because their study did not directly measure perceived azimuth angle, Foley and colleagues (2004) remained neutral about whether perceived azimuth direction was actually expanded, stating:

> The common assumption is that perceived direction re straight ahead equals physical direction, but there is evidence that perceived direction may be slightly greater than this and that consequently perceived visual angles may be slightly greater than the corresponding physical angles... Either assumption can be incorporated into the model without affecting the nature of the space. (p. 153)

Several earlier papers by Foley (e.g., Foley, 1965, 1972; see also Bock, 1993) suggested exaggeration in perceived azimuth angle/direction. However, because those studies were conducted in dark environments, the angular distortions implied in those studies could have been due to impoverished visual information. Philbeck, Sargent, Arthur, and Dopkins (2008) reported little bias in angular judgments of azimuth in near space in a lighted indoor environment, but several other authors have consistently found evidence of exaggeration in perceived visual direction (e.g., Fortenbaugh, Sanghvi, Silver, & Robertson, 2012; Haun, Allen, & Wedell,

2005; Higashiyama, 1992). Higashiyama (1992) directly examined perceived vertical and horizontal visual angles in an outdoor setting and found evidence of large angular expansion (by as much as 1.6 with a viewing distance of 30 m). One limitation of his study was that he used markers on the face of a building to indicate the visual angles to be estimated. He did find greater angular expansion in elevation than in azimuth, but since all the markers (for all the vertical and horizontal visual angles he tested) were visible to the participants throughout the experiment, the angular estimates may have been confounded with size judgments scaled by the features of the building such as the windows. A more complete quantitative review of prior evidence concerning azimuthal bias will be presented in the General discussion.

The purpose of the present study was to establish a mathematical model to describe the perception of azimuth direction in an outdoor environment. To accomplish this, we systematically measured the perceived azimuth direction in an outdoor open field under full cue viewing conditions. Both an explicit measure (numerical estimation, Experiment 1) and an implicit measure (ground extent matching, Experiment 2) were used. As we will show, the two measures provided converging evidence that allowed us to model the perceived azimuth direction using a linear function. Because there was a small but systematic overall shift between the results of the two experiments, in Experiment 3, we investigated whether this discrepancy could be partly due to a retinotopic, horizontal vertical illusion. The azimuth model established in the present study strengthens the explanation power of the *Angular Expansion Hypothesis* (Durgin & Li, 2011a) which has already offered quantitative accounts for several well-documented biases in space perception, including the uphill/downhill geographical slope exaggeration, the egocentric distance foreshortening, the exocentric distance anisotropy, and the bias in perceived distance-height ratio (Durgin, Li, & Hajnal, 2010; Li & Durgin, 2009, 2010, 2012a, 2013; Li et al., 2011, 2013). Incorporating the azimuth model into the angular expansion hypothesis helps extend it beyond slants and distances in the sagittal plane (see also Li & Durgin, 2013).

Experiment 1: Explicit estimation of azimuth direction

Previous work has justified using magnitude estimation in the study of perceived slant, visual direction, and 2D orientation (e.g., Dick & Hochstein, 1989; Durgin et al., 2010; Durgin & Li, 2011a, 2011b; Li & Durgin, 2010). In the present study, to assess perceived azimuth direction, participants were asked to give numerical estimates of angular separation between a reference marker (always at 15 m in the straight ahead direction) and a target (at 5 or 15 m). We used angular separations in the range of 0°–48° (with both leftward and rightward azimuth direction). In order to be able to differentiate between exaggerated perception of head (or eye) rotation and a more general visual directional bias, we manipulated whether participants were allowed to move their head or eyes during the task. There is evidence suggesting that perceived egocentric distance to a target on the ground is not affected by whether the observer's gaze is directed to the target or not (Gajewski, Wallin, & Philbeck, 2014a, 2014b). We suspect that perceived azimuth direction may also be unaffected by gaze/head direction.

Method

Participants

Thirty-five undergraduates from Swarthmore College (20 male, 15 female) participated in this experiment for payment. All the participants had normal or corrected-to-normal vision. All the experimental procedures used in the present study were approved by the local research ethics committee.

Apparatus

A mobile eye-tracker (Positive Science, LLC, New York, NY) was used to monitor the participants' eye and head movements. The eye-tracker is composed of two digital camcorders, one for monitoring the visual scene, the other for monitoring the eye/pupil position. With a standard five-point calibration procedure, the eye fixation positions relative to the visual scene can be measured offline using the Yarbus eye-tracking software with subdegree precision.

Stimuli and task

The experiment was conducted in a grass field at the campus of Swarthmore College. The participants stood facing the field from one side. There were trees and buildings at a distance of a few hundred meters. A red disk (15 cm in diameter) attached to the top of a thin stake (1.6 m tall) was set 15 m away in front of the participants, which served as a reference for the direction of straight ahead (Figure 4, solid circle). Twenty-four possible locations were used to place the target (Figure 4, open circles), which corresponded to six azimuth directions to the left and to the right (±8°, ±16°, ±24°, ±32°, ±40°, and ±48°) at two viewing distances (5 m, 15 m). The locations were marked so that the experimenter could quickly find them, but with

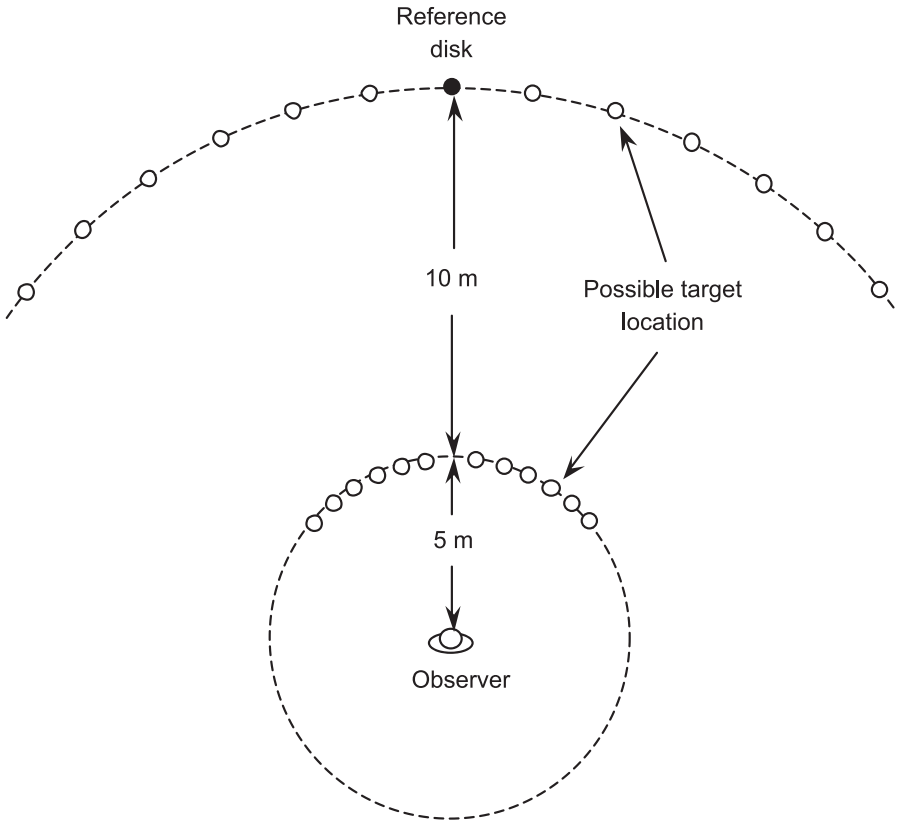

Figure 4. Diagram of the experimental setup used in Experiment 1 (top view). The participants gave verbal estimations of angular deviation from the target location (open circles) to straight ahead (direction to the solid circle). Only one target location was visible on each trial.

markers invisible to the participants. In each trial, the experimenter stood at one of the target locations and served as the target. The participants' task was to estimate, in degrees, the angular deviation from the experimenter to straight ahead.

Design and procedure

Three viewing conditions were used between subjects. In the *Head Free* condition, participants were allowed to move their head or eyes as they wished. In the *Head-Fixed* condition, participants rested their head on a chinrest (the height of the chinrest was adjusted for each participant to ensure comfort.) The participants were asked to face their head toward the red disk at all times during the test, but they were allowed to move their eyes (i.e., gaze) freely. Finally, in the *Gaze-Fixed* condition, participants also rested their head on the chinrest and faced toward the red disk, but they were instructed to always keep their eyes fixated on the red disk during the test. Each participant was tested in one of these conditions: Eleven participants were assigned to the *Head-Fixed* condition; twelve participants were assigned to each of the other two conditions. Before the tests, participants were instructed using a diagram showing an overview of the sort of angles they were to be judging. Once it was certain that the participants understood the task, they were fitted with the mobile eye tracker. A standard five-point eye movement calibration was completed before the estimation began. At the beginning of each trial, the participants were asked to close their eyes while waiting for the experimenter to relocate to the new target location (the order of the locations was prerandomized for each participant). Then, the participants were signaled to open their eyes and to make their numeric angular estimate. Two-way radios were used for communication when necessary at the larger distances. After each estimate was recorded, the participants closed their eyes, and the experimenter moved to the next target location.

Results

An initial examination of the overall results (with the mean verbal estimates collapsed across all viewing conditions and distances, but maintaining the sign of the angular deviations) suggested a fairly linear relationship between the perceived and actual azimuth

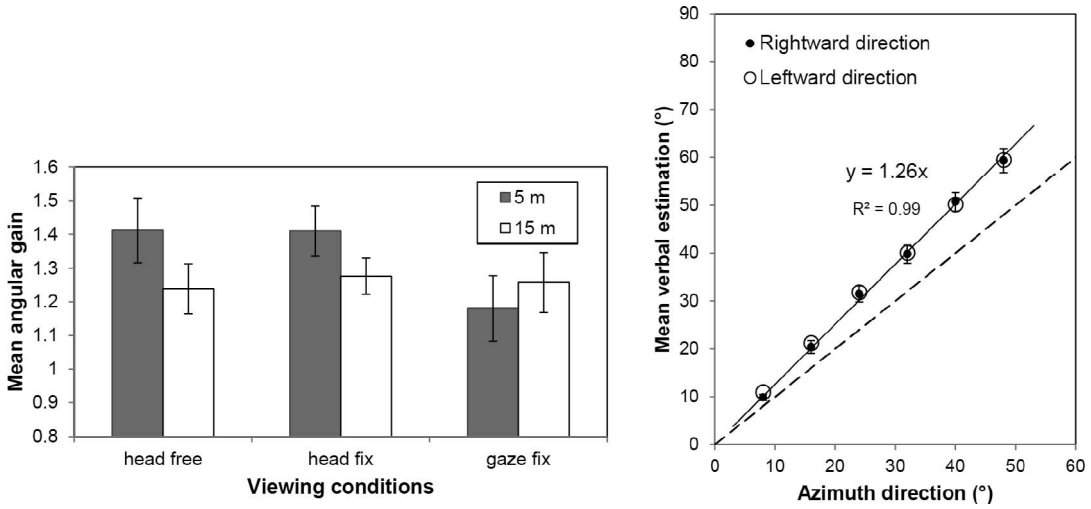

Figure 5. Results of Experiment 1. Left: mean gain of perceived azimuth direction as a function of viewing condition and viewing distance. Standard error bars are shown. Right: mean verbal estimates of perceived azimuth direction (collapsed across viewing conditions) as a function of actual azimuth direction. Standard errors are shown only for data dots of the rightward azimuth direction for clarity.

directions. In order to conduct an analysis to test for possible effects of viewing condition and distance, for each participant, we first computed the angular gain (i.e., the slope of a linear regression) for targets presented at each viewing distance.

A mixed 3 between (Gaze Restriction: Gaze-Fixed, Head-Fixed, and Head Free) × 2 within (viewing distance: 5 and 15 m) factor ANOVA was conducted on the individual participant's gain data at each distance. The effect of Viewing Distance on angular gain differed as a function of Gaze Restriction, $F(2, 32) = 7.90$, $p = 0.0016$. This interaction is shown in Figure 5 (left). Posthoc tests, with Bonferroni correction ($\alpha = 0.017$), confirmed that the gain was reliably higher when the target was nearer (i.e., 5 m), when either eye movements were allowed (*Head-Fixed*), $t(10) = 2.92$, $p = 0.015$, or when both head and eye movements were allowed (*Head Free*), $t(11) = 5.05$, $p < 0.001$; but that there was no effect of viewing distance when gaze was required to be fixed on the reference disk throughout each trial, $t(11) = 1.27$, $p = 0.23$. Recall that the reference point, to which targets were compared, was at 15 m. Because the angular gain was unaffected by viewing distance when gaze refixation on the targets was not allowed, it seems possible that the higher gains for the 5 m condition might be artifacts resulting from changes in fixation between the 5 m target and the 15 m reference—or, more specifically, due to the greater physical distance between the ground contact points of the near targets and the far reference post—which would have been more visually accessible when gaze could shift. Although we cannot rule out the possibility that the angular gain would have been higher for nearer targets even if the reference point were at the nearer distance, there is no support for this idea in the literature (see General discussion). Because Higashiyama's (1992) data suggest that there may be contaminating effects of linear distances on azimuthal estimation, and because there was no effect of viewing distance in the *Gaze-Fixed* condition, it seems safest to assume that something unusual is happening in the other conditions. In particular it seems likely that the data from the 5 m distance with a 15 m reference distance may contain artifacts based on increased linear ground extents that became particularly salient when fixation was not maintained at the far target and interfered with the evaluation of angular extent. We therefore focus our analysis on the 15 m condition alone, because viewing condition had no effect here. Mean verbal estimates for the 15 m targets (collapsed across viewing conditions) are plotted for the rightward and leftward viewing directions separately (Figure 5, right), which shows consistent overestimation in perceived azimuth. A linear fit to all 12 points indicates an angular gain of 1.26 in the perceived azimuth function.

A model of the perceived azimuth direction

The primary purpose of the present study is to model perceived azimuth direction. The verbal estimation data in Experiment 1 suggest that the perceived azimuth direction can be approximated by a linear function of the actual azimuth direction, with an angular gain of 1.26. If we leave the gain to be a free parameter, the azimuth model will take the form of Equation 1.

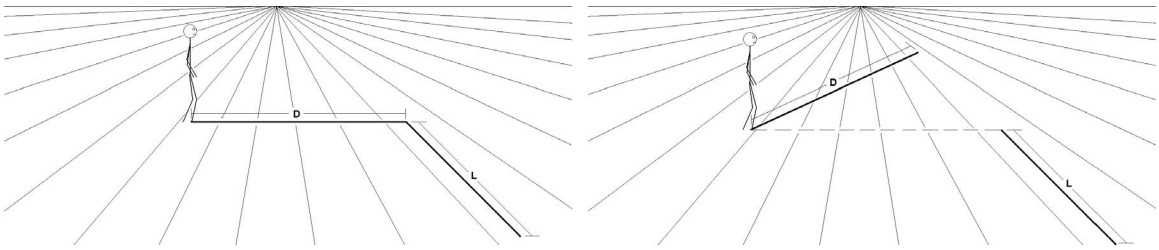

Figure 6. Diagrams showing the egocentric-frontal, extent-matching tasks. In the standard version (left), the observer set the egocentric distance, D, between himself/herself and the frontal extent, L, to match the length of the frontal extent. In the modified version (right), the observer set the length of an egocentric distance, D, along a diagonal path to the frontal extent, L, to match the length of the frontal extent. Note, in both cases, the egocentric and frontal extents are always on the ground plane.

$$\varphi' = k\varphi \quad (1)$$

Where φ' is the perceived azimuth direction, φ is the actual azimuth direction, and k is a constant gain factor. The results of Experiment 1 suggest that k is 1.26.

Discussion

The results of Experiment 1 suggested that the numerically estimated azimuth direction can be approximated by a linear function of the actual azimuth direction in the range we tested (−48° to 48°), with the best estimated angular gain being 1.26. Whereas in previous studies, we have not differentiated between gaze direction and visual direction, the present results support the conclusion that visual direction is expanded even when the gaze directions are fixed. This is consistent with the observations by Gajewski, Wallin, and Philbeck (2014b; see also Gajewski, Philbeck, Pothier, & Chichka, 2010) that showed that visual ground distance is perceived similarly even with visual presentation too brief for eye movements to occur.

Although numerical estimation tasks would require cognitive translations of perceptual variables into numbers, prior studies of slant and spatial orientation perception using numerical estimation have demonstrated rather consistent spatial patterns across multiple methods. For example, spatial biases are similar for surface slant and 2D line orientation whether orientation is numerically estimated relative to horizontal as zero or estimated relative to vertical as zero (Durgin et al., 2010; Durgin & Li, 2011b). Moreover, numeric angular estimates are also fairly consistent with nonverbal measures of space perception.[2] For example, angle (and direction) bisection tasks show that the midpoint is biased in the same way as the estimated 45° point (Durgin & Li, 2011a; Durgin et al., 2010). The consistency of numeric estimates in orientation is probably because educated adults (such as college students) share a common conceptual scale of orientation with fixed numeric anchors (0°, 45°, 90°, etc.). For these reasons (and others), we think that numeric estimates of perceived direction and orientation provide an important source of information for estimating biases in angular variables.

Li and Durgin (2010) have shown that numerical estimation of perceived optical slant was substantially consistent with implicit slant estimation based on data from an aspect ratio task. Li et al. (2011) also showed that numeric estimates of angular elevation in the sagittal plane (Durgin & Li, 2011b; Li & Durgin, 2009) predict findings from behavioral measures such as perceptual matching of height and egocentric distance These same errors in perceptual matching of height and egocentric distance were found even when participants had expertise that allowed them to verbally estimate egocentric distance more accurately (Durgin, Leonard-Solis, Masters, Schmelz, & Li, 2012). Thus, spatial comparisons in locomotor space can act as converging measures of angular bias. We adopted a similar approach in Experiment 2, using ground-extent-matching as an implicit measure of perceived azimuth direction. The extent-matching task can be an important source for providing converging evidence.

Experiment 2: Implicit measurement of perceived azimuth direction

As we have mentioned in the Introduction, the data from egocentric-to-frontal, extent-matching task have suggested overestimation in perceived azimuth direction (e.g., Foley, 1972; Higashiyama, 1996; Li et al., 2011). However, in the standard versions of this egocentric-frontal matching task, only a single azimuth direction, the perceived 45°, is measured because the task amounts to forming an equilateral right triangle, with the observer at one of the acute angles (Figure 6, left panel). Li et al. (2013; see also Philbeck, O'Leary, &

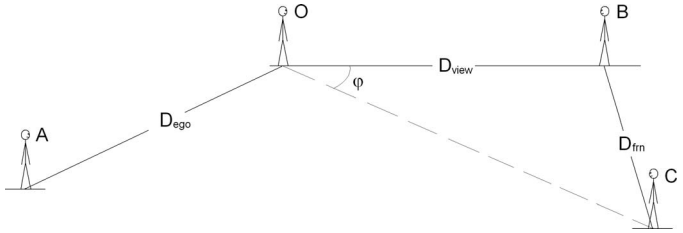

Figure 7. Diagram depicting the setup in Experiment 2. Two experimenters (B and C) served as the targets for a frontal extent (D_{frn}). Their distance (D_{view}) to the participant (O) varied from trial to trial. The participant was asked to adjust the position of a third experimenter (A) along an opposite-viewing direction so that the egocentric distance (D_{ego}) from the participant to experimenter A appeared the same as the frontal extent, D_{frn}. Note, all the experimenters were on a level ground.

Lew, 2004) used a modified version of the egocentric-frontal matching task, in which the frontal extent was matched to an egocentric distance along a line of sight that was oblique to the frontal extent (Figure 6, Right panel). The advantage of the modified version of the extent-matching task is that the size of the frontal extent becomes independent to its viewing distance, so that multiple azimuth directions can be assessed.

In Experiment 2, we developed a variation of the egocentric-frontal matching task used by Li et al. (2013) to derive an implicit estimate of perceived visual direction. In this variant, the frontal extent was matched to an egocentric distance at a far oblique viewing direction (so as to avoid configural judgments such as those that might occur when both the egocentric and frontal extents are visible in the same part of the visual field). Additionally, we used frontal extents that were presented at several different viewing distances. In conjunction with our quantitative model of perceived egocentric distance (Durgin & Li, 2011a), this extent-matching task can be interpreted as providing an implicit measure of perceived azimuth direction (Appendix).

Method

Participants

Nineteen undergraduates from Swarthmore College (11 male, eight female) participated in this experiment for payment. None had participated in Experiment 1. All participants had normal or corrected-to-normal vision. All the procedures used in this experiment were approved by the local research ethics committee.

Stimuli and task

The experiment was conducted in a large, flat, outdoor grass field (200 m × 150 m). Participants stood at the central area of the field. Their task was to match a frontal extent (D_{frn}) to an egocentric distance (D_{ego}) at far oblique viewing direction (Figure 7). Combinations of a 9-m frontal extent with three viewing distances (21, 30, and 42 m) and combinations of a 15-m frontal extent with another three viewing distances (27, 42, and 54 m) were tested. These combinations correspond to six azimuth directions (i.e., 12.1°, 15.5°, 16.7°, 19.7°, 23.2°, and 29.1°). Each of the combinations was presented twice to each participant (one trial with a small initial D_{ego} and one trial with a large initial D_{ego}). Because only two physical frontal extents (i.e., 9 and 15 m) were presented in these combinations, we worried that participants might notice repetition, which could introduce more cognitive artifacts into their responses. To minimize this possibility, we added in six filler trials, in which the viewing distance to the frontal extent was one of 9, 15, 18, 27, 30, and 54 m, while the size of the frontal extent was randomly varied. No data were actually recorded on these filler trials to avoid slowing the experiment. The frontal extents in the filler trials were chosen with the constraint that their corresponding azimuth directions were always between 6° and 45°. Thus, each participant did 18 trials of extent-matching, including 12 test trials, for which matches were carefully measured, and six filler trials intended to disguise the experimental design. The order of the test trials was randomized for each participant, with fillers on trial 1, 4, 7, 10, 13, and 16. The first trial for each participant was a filler trial that also served as a practice trial. The standing location of the participant was fixed throughout the experiment. The standing locations of experimenters B and C in the test trials were marked in advance using labeled markers set in the grass that can be easily found by the experimenters, but were not visible from where the participants stood.

Procedure

The participants were instructed with the help of a diagram showing an overview of the matching task. Once it was certain that the participants understood the task, the experiment began. At the beginning of each trial, the participants were asked to hold a foam board to cover their face and chest while facing experimenter A, so that they could not see the experimenters. The foam board, in conjunction with a laser range finder, was also used to measure D_{ego}. Once all experimenters were in position, experimenter A signaled the participants, by voice, to start the trial. Two-way radios were used to facilitate communication, especially at farther distances. The participants, then, lowered the foam board and started to direct experimenter A to move closer or farther away. They were allowed to look back and forth between experimenter A and B and C at will. After the participants were satisfied with their distance

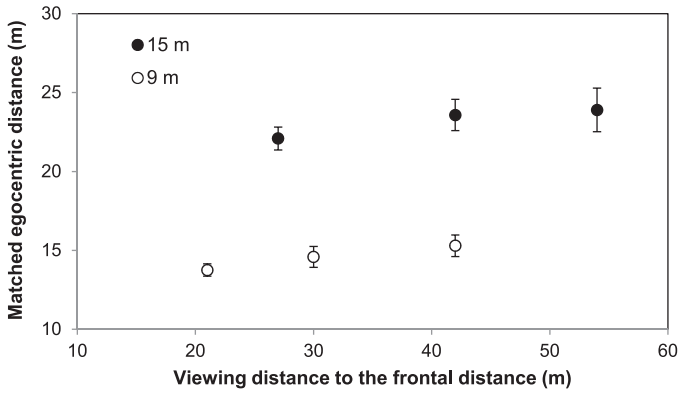

Figure 8. Results of Experiment 2. Mean matched egocentric distance as a function of viewing distance and of size of frontal extent. Standard errors are shown.

adjustment, they turned to experimenter A and covered their face and chest with the foam board again. Experimenter A, then, measured D_{ego}, and all experimenters relocated to the predetermined locations for the next trial. Then, a new trial began.

Results

Figure 8 shows the mean matched egocentric distance as a function of viewing distance and of size of the frontal extent (9 m and 15 m). We conducted a within-subjects ANOVA with viewing distance (Near, Medium, or Far) and Frontal extent (Short or Long) as factors. There was, of course, a highly reliable effect of Frontal extent that longer matches were made for longer frontal extent, $F(1, 18) = 240.7$, $p < 0.0001$. However, there was also a reliable effect of viewing distance, $F(2, 36) = 6.14$, $p = 0.0051$. Examination of Figure 8 reveals that for the same-sized horizontal extent, the matched egocentric distances were greater at larger viewing distances. Such a result may tend to seem inconsistent with a constant angular gain, but it could also be a sign of overconstancy due to cognitive compensation (Carlson, 1962) or other factors not accommodated by the present model (e.g., Higashiyama, 1992).

The purpose of Experiment 2 was to use the extent-matching task as an implicit measure to assess the perceived azimuth direction. Details of deriving perceived azimuth direction from the extent-matching task are given in the Appendix. Deduced perceived azimuth direction is plotted as a function of actual azimuth direction in Figure 9 (open circles). The best linear fit showed a slope of 1.14 and an intercept of 6.5°. For comparison, the result from Experiment 1 is also plotted as open triangles. It is clear that the trend of the results from the two experiments was fairly

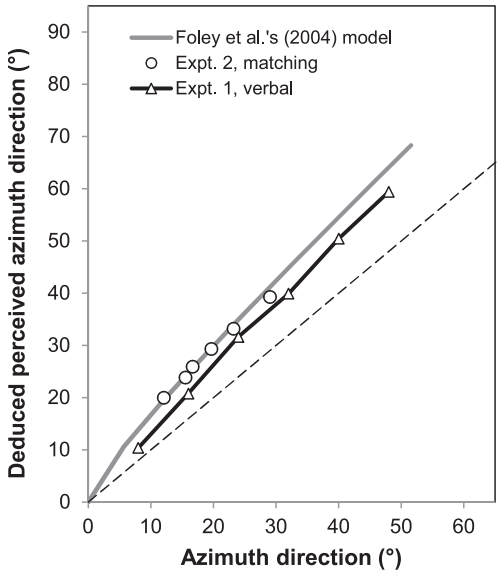

Figure 9. The results of Experiment 2 (the matching task) plotted in terms of the deduced perceived azimuth function (open circles). For comparison purpose, the deduced azimuth function from the explicit measure of Experiment 1 (open triangles) and from the study of Foley et al. (2004) (gray line) are also shown.

consistent, but the perceived azimuth function derived from the matching data is apparently shifted upwards by several degrees from the directly measured azimuth function. To further compare the present results to that of Foley et al. (2004), the imputed azimuth function developed by Foley et al. is also plotted in Figure 9 (gray line). This imputed azimuth function was derived from Foley et al.'s distance estimation data (it was originally shown in figure 5 of Foley et al.'s paper). It is clear that the azimuth function derived from the extent-matching task of Experiment 2 is nearly identical to the findings of Foley et al. Therefore, both the size perception data (i.e., Experiment 2 and Foley et al.) and the explicit angular estimation data (Experiment 1) seem to agree that perceived azimuth direction is exaggerated.

Discussion

Experiment 2, using the modified egocentric-frontal, extent-matching task, replicated Foley et al.'s (2004) finding, based on numeric estimation, that perceived azimuth direction may be overestimated. The results were also fairly consistent with the explicit measure of perceived azimuth direction in Experiment 1. But, there was an apparent overall shift between the results based on distance judgments (i.e., Experiment 2 and Foley et al.) and the findings based on explicit direction estimations (Experiment 1). If we assume that the

azimuth function must have a zero intercept (i.e., perceived straight ahead direction is accurate), then the explicit direction judgment data indicate a linear azimuth function, while the distance judgment data suggest a nonlinear azimuth function. (Foley et al.'s proposed azimuth function contained both a linear component and a power function component). It might be that either measure has some bias in it or that other factors contribute to either measure. For example, it might be that the numerical estimation task suffers from cognitive factors that produced an illusion of linearity. Conversely, it also could be that distance estimation of frontal ground extents show distance-dependent overcompensation.

In particular, it seems possible that the apparent upward shift in the deduced azimuth functions, based on the distance tasks, was partly due to the overcompensation of perceived size (the size overconstancy effect, Carlson, 1962; Granrud, 2012; Granrud et al., 2009). That is, most adults know that the size of an object appears smaller at farther distance. Under objective instruction, people tend to overcompensate in the estimates of perceived size, especially when the target object is viewed at a large distance. Such overcompensation is suggested by Figure 8, in which the apparent size of the same-length frontal extent was judged longer when viewed at a farther distance. If the matching of frontal extents in Experiment 2 (and also the estimation of ground extents in Foley et al.'s, 2004 study) included overcompensation, then the actual perceived azimuth direction should be smaller than the deduced values, and would be more similar to those directly measured in Experiment 1.

However, another straightforward source of bias in the extent-matching task might be the horizontal vertical illusion (HVI). When comparing an egocentric distance to a frontal extent, the egocentric distance would correspond to a vertical line on the retina, whereas the frontal extent would correspond to a horizontal line. If vertical lines are overestimated by about 4%–6% relative to horizontal lines, as is typically found in the HVI, we would expect the egocentric settings to be slightly shorter than they should be. Similar bias could also affect Foley et al.'s model because that model was based on the estimation data of both egocentric and frontal extents. However, such a consideration shouldn't apply in the angular estimation task because only a single axis is considered. In a previous study of perceived aspect ratio of configurations presented on surfaces slanted in pitch or in yaw, we found evidence of a small (6%) but reliable HVI in extent matching (Li & Durgin, 2013). Therefore, in Experiment 3, we decided to investigate whether some of the differences between the angular gain estimates derived in Experiments 1 and 2 might be partly due to the HVI affecting the matches in Experiment 2.

Experiment 3: Egocentric-frontal extent matching with sideways observers

One way to study the effect of HVI on the extent-matching task is to tilt observers sideways so that their retinal image will be reoriented by 90°. This should reverse the HVI effect on the matching data (Avery & Day, 1969; Klein, Li, & Durgin, in press; Künnapas, 1958; Prinzmetal & Gettleman, 1993). If the HVI affected the results of the extent-matching in Experiment 2, then when we tilt the observers to their side, their judgments on the extent-matching task should differ from those when they stand upright. Moreover, if we mathematically remove the HVI effect from the matching data, the difference in the extent-matching results between the upright and sideways conditions should disappear. In Experiment 3, we tested this hypothesis by having half of the participants lie sideways at eye level while they did an egocentric-frontal, extent-matching task.

Method

Participants

Thirty-five undergraduates from Swarthmore College (18 male, 17 female) participated in this experiment. Seventeen were assigned to the *upright* condition and the other 18 were assigned to the *sideways* condition. None of them had participated in Experiment 1 or 2. All had normal or corrected-to-normal vision. The procedures used in this experiment were approved by the local research ethics committee.

Stimuli and task

The experiment was conducted in a different open grass field because the large grass field where we did Experiment 2 was now under construction. This field was relatively small (about 40 m × 50 m) and was surrounded by trees, buildings, and a parking lot. The standard egocentric-frontal, extent-matching task (i.e., Figure 6, left panel) was used, because when participants lie on their side, they cannot easily turn to look in a different direction. Two experimenters stood in front of the participants to form the frontal extent. The positions of the participant and the two experimenters formed a right triangle with the participant being always at an acute angle vertex. The participants were asked to direct

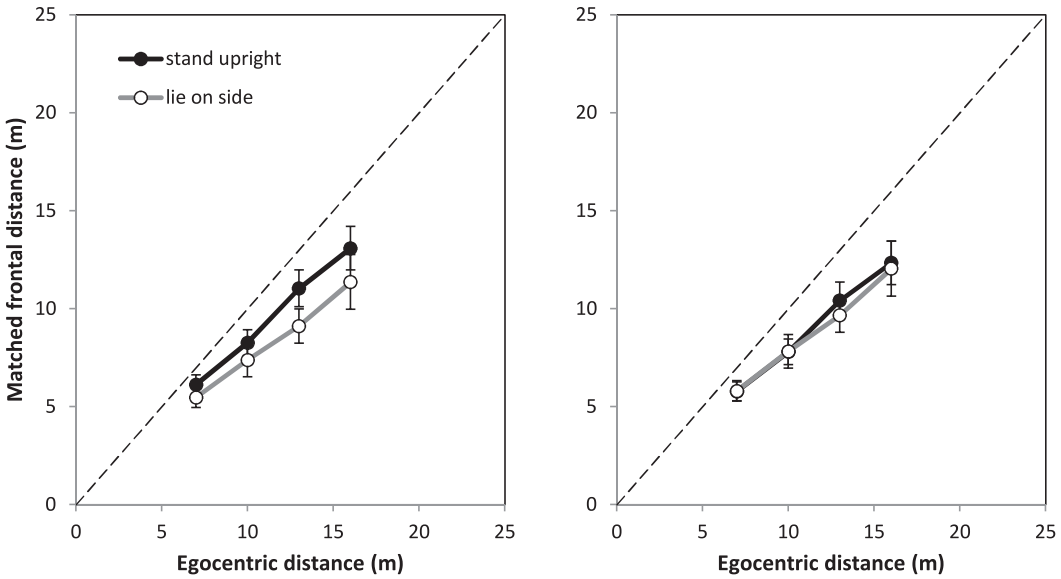

Figure 10. The results of Experiment 3. Left panel: matched frontal extent as a function of egocentric distance and of body orientation (upright vs. sideways). Right panel: the same matching data after the presumed effect of the (6%) HVI was removed from individual participants' matched frontal extents. Standard deviations are shown.

the experimenter at the other acute angle vertex to move closer to (or farther away from) the experimenter at the right angle vertex, so that the distance between the two experimenters (the frontal extent) appeared the same as the distance between the participant and the experimenter at the right angle vertex (the egocentric distance). Two *Body Orientations* (upright vs. lying sideways) were examined (between subjects). Four egocentric distances (7, 10, 13, and 16 m), combined with two initial frontal extents (small vs. large), were tested with each participant. A wooden cart was built to support sideways participants approximately at eye height (see Klein et al., in press). A cot was placed on top of the cart, and the participants lay on the cot on their side, with their head resting horizontally on a pillow. The eyes of the participants in the sideways condition were about 1.7 m above ground.

Procedure

The participants were instructed with the help of a diagram showing an overview of the task. The instruction to the sideways participants was given after they were lying on the cot. Once it was certain that the participants understood the task, the trials began. A third experimenter stood near the participants throughout the experiment. At the beginning of each trial, the third experimenter blocked the view of the participants with a board, which was removed after the other two experimenters were in position. Then, the participants started to adjust the position of the experimenter at the acute angle vertex. Two-way radios were used to facilitate communication. Once the participant was satisfied with the adjustment, their view was blocked again, while the experimenters recorded the matched distance and relocated to new initial positions for the next trial. Then, a new trial began. The initial locations of the experimenters were marked in advance with labeled markers set in the grass that were not visible to the participants.

Results

Figure 10 (left panel) shows the mean matched frontal extent as a function of viewing (i.e., egocentric) distance and body orientation. As we have reasoned above, if the HVI affected extent-matching, then we should expect differences in the matching results between the two body-orientation conditions. A mixed 2 between (*Body orientation*: upright or sideways) × 4 within (*Egocentric distance*: 7, 10, 13, or 16 m) × 2 within (*Initial frontal extent*: small or large) ANOVA confirmed that there was a reliable effect of *Body orientation* such that longer matches were made by upright participants, $F(1, 33) = 31.4$, $p < 0.0001$. There was also a reliable effect of *Egocentric distance*, $F(3, 99) = 574.7$, $p < 0.0001$, and a reliable effect of *Initial frontal extent*, $F(1, 33) = 13.68$, $p < 0.001$. An interaction between *Body orientation* and *Egocentric distance* was also found, $F(3, 99) = 7.17$, $p < 0.001$. These results are consistent with our assumption. That is, if the HVI caused a slight overestimation in perceived egocentric distance relative to perceived frontal extent, then the matched frontal extent would be set slightly larger by the upright participants relative to that set by the sideways participants. Moreover, if the

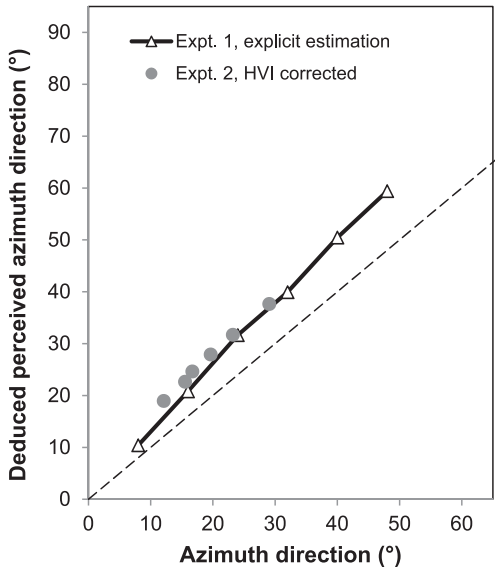

Figure 11. Replot of the results of Experiment 1 (open triangles) and Experiment 2 (gray circles), after applying a correction for the HVI to the extent-matching data of Experiment 2.

difference in the extent-matching results of Experiment 3 (between the upright and sideways participant) was caused by HVI, then we should expect this difference to disappear once the effect of the HVI is removed from the matching data. Li and Durgin (2013) found that a HVI with a magnitude of about 6% affected their aspect ratio matching task. Therefore, we assume a HVI with similar magnitude may have affected the present extent-matching task. To remove the effect of this HVI, we modified the individual participant's matched frontal extent. For the upright participants, they may have set the frontal extent slightly too long, so we divided their matched frontal extent by 1.06 (i.e., the magnitude of the assumed HVI). For the sideways participants, they may have set the frontal extent too short, so we multiplied their matched frontal extent by 1.06. After this HVI correction, the extent-matching results of the two body orientation groups became very similar (Figure 10, right panel). The same ANOVA conducted on the modified matching data showed that the main effect of the *Body orientation* disappeared, $F(1, 33) = 1.13$, $p = 0.293$; and that the interaction between *Body orientation* and *Egocentric distance* also disappeared, $F(3, 99) = 2.49$, $p = 0.065$; but that the effect of *Egocentric distance*, $F(3, 99) = 567.6$, $p < 0.0001$, and the anchor effect of the *Initial frontal extent*, $F(1, 33) = 13.28$, $p < 0.001$, remained reliable.

Discussion

The perceived azimuth direction functions derived from the results of Experiments 1 and 2 were slightly different (i.e., Figure 9, open circles vs. open triangles). We proposed that at least two factors may have contributed to this discrepancy: overconstancy and the HVI. In Experiment 3, we tested whether the HVI could cause a measurable change in the extent-matching task if we tilted half the observers sideways (which should reverse the HVI effect on the matching task). The results were consistent with our hypothesis.

Because the results from Experiment 3 confirmed that an HVI (with a magnitude of about 6%) seems to affect extent-matching tasks (see also Li & Durgin, 2013), we can now mathematically remove this effect from the matching results of Experiment 2. Because all participants were upright in Experiment 2, we simply divided their matched egocentric distance by 1.06, on the assumption that the HVI has resulted in a slight distortion of perceived egocentric distance relative to frontal extent. After this HVI correction for each individual participant, we regenerated the implied azimuth function (Figure 11, gray circles) and plotted it with the azimuth function derived from the explicit direction estimation of Experiment 1 (Figure 11, open triangles). It is clear that after taking the HVI into account, the two azimuth functions have become much more similar. There are still residual differences between the two functions, but these additional differences might have resulted from size overconstancy (Carlson, 1962) in the extent judgment process. It is also possible that additional unspecified perceptual factors contributed to this discrepancy.

The strategy employed here to eliminate the HVI assumes that there is a retinotopic HVI that increases the ratio between perceived egocentric and frontal distances for upright observers and decreases the ratio for sideways observers. We have recently employed the same strategy for the large-scale HVI to show that there is a large, ground-based component and a smaller, retinotopic component of the outdoor HVI (Klein et al., in press).

General discussion

In the present study, we measured perceived azimuth direction using two very different tasks—an explicit numerical estimation task (Experiment 1), and an extent-matching task that implicitly assesses perceived azimuth direction (Experiment 2). The results from both experiments are consistent with the hypothesis that perceived azimuth direction is overestimated. The distance results are quite consistent with the exocentric distance estimation data of Foley et al. (2004), which also implied overestimation in perceived azimuth angles. This consistency seems important given that we used a nonverbal method to measure perceived extent,

whereas Foley et al. used numeric estimates. Thus, the present work provides strong converging evidence concerning the estimated size of exocentric ground extents. Moreover, based on the results of Experiment 3 where some observers made size comparisons while lying sideways, we have suggested that one small additional source of bias in both of these types of distance judgments is a retinotopic HVI.

Whereas Foley et al. (2004) proposed that angular expansion might be a mathematical fiction in their model, our numerical estimation data suggest that at least part of the angular expansion assumed in Foley et al.'s model is evidently present in the direct estimations of visual azimuth direction (relative to straight ahead). In fact, the exaggeration in perceived visual direction in azimuth fits well with the framework of the angular expansion hypothesis (i.e., Durgin & Li, 2011a; Li & Durgin, 2012a) which proposes that several well-documented biases in space perception can be quantitatively understood by assuming perceptual biases in two other angular variables—visual direction along the sagittal plane, and optical slant. For example, it has been shown that exaggeration in angular elevation (both upward and downward relative to straight ahead) can quantitatively explain egocentric distance foreshortening (Durgin & Li, 2011a), bias in perceived egocentric distance to height ratio (Li et al., 2011), and downhill slope exaggeration (Li & Durgin, 2009); and that overestimation in perceived optical slant can account for uphill slope exaggeration (Durgin et al., 2010; Li & Durgin, 2010, 2013), exocentric distance anisotropy (Li & Durgin, 2010, 2013; Li et al., 2013), and compressive foreshortening in the perceived exocentric in-depth extent (Li & Durgin, 2012a). Incorporating the new azimuth model (i.e., Equation 1) into the angular expansion hypothesis confirms that even findings of anisotropy in size perception of ground extents (such as reported by Foley et al.) can be accounted for largely by angular bias. Moreover, Klein et al. (in press) have recently found evidence that the fact that the angular gain of perceived visual direction is apparently different for azimuth (1.26) than for elevation (1.50) accounts for the very large perceptual anisotropy between horizontal and vertical extents (about 20%) that has been reported for large outdoor objects (Chapanis & Mankin, 1967).

With regard to perceived slant, evidence of consistent and systematic orientation biases have been reported in the haptic perception of slant (Durgin & Li, 2012; Hajnal, Abdul-Malak, & Durgin, 2011; Shaffer & McManama, 2015) as well as in the proprioception of hand orientation (Li & Durgin, 2012b). With respect to perceived azimuth direction, angular scale expansion has additionally been discovered in the vestibular perception of heading direction (e.g., Cuturi & MacNeilage, 2013). Thus, this seems to be a general perceptual strategy that extends beyond vision to the multimodal perception of locomotor space.

Although there is a great deal of literature on the possibility of visual error in perceived angular direction in near space (e.g., Bock, 1993; Fortenbaugh, Sanghvi, Silver, & Robertson, 2012; Temme, Maino, & Noell, 1985), much of this literature can be hard to interpret in terms of the *perceived* angular direction (i.e., in degrees from fixation). For example, Bock (1993) used pointing to show angular expansion (overpointing) in perceived azimuthal direction. But this kind of measure compares two unknowns (perceived visual direction and perceived pointing direction). Even if pointing direction were accurately aligned with visual direction, it would be impossible to know the perceived direction of either the pointing direction or the visual direction from this method, though it would imply that the two percepts were consistent with each other. The difference between pointing direction and visual direction observed by Bock (which disappeared when gaze was toward the peripheral target) might indicate something about transformations between visual and pointed direction, but this is only speculative. In what follows, we seek to summarize prior relevant data concerning perceived azimuthal direction that can be interpreted as estimating bias.

Fortenbaugh et al. (2012, following the method of Temme et al., 1985) had people make numeric or spatial judgments of perceived eccentricity where they defined the range of their scale (0–100 scale units) in terms of the angular distance from the central fixation point to the edge of the visual field. Because they did not assess perceived direction to the edge of the visual field, their method would not be able to detect any overall linear bias, such as we (and Higashiyama, 1992) have observed. This is because Fortenbaugh et al. assumed in their interpretation of their data that there is no error in the perceived direction to the extreme edge. This means their method can best pick up nonlinear components (nonuniform expansion or compression) between fixation (assumed to be zero) and the nominal edge (assumed to be perceived accurately). If the perceived direction to the edge of the visual field were exaggerated, however, their method could seem to show underestimation (relative to that edge) even when overestimation was present (overall). When no far boundary was visible, Fortenbaugh et al. did primarily observe expansion away from the fovea in azimuth and even greater expansion in angular elevation. When they added a visible outer boundary, the boundary also seemed to repel the judgments. Nonetheless, for monocular judgments of azimuth in the temporal direction, when no visible boundary was present, it is possible to interpret the azimuth data of Fortenbaugh et al. (2012) in terms of a presumed/perceived 90° limit of the field of view.[3] When so

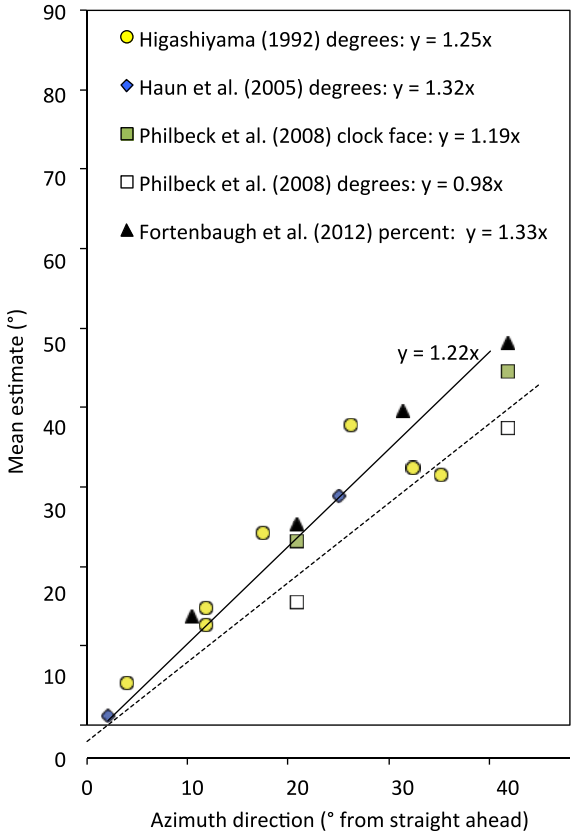

Figure 12. Plots (limited to azimuthal eccentricities of 40° or less) of the results of several previous studies measuring perceived azimuthal direction. The data of Higashiyama (1992, Experiment 3) represent verbal estimates in degrees of horizontal intervals. Clock-face estimates and verbal estimates diverged in the study of Philbeck et al. (2008), and so are plotted separately (see text). The data of Fortenbaugh et al. (2012) are limited to temporal eccentricities where the (unbounded) monocular visual field is presumed to extend to 90°. The data of Haun et al. (2005) were from memory, but appear consistent with judgments from perception. Gain values for the data from each study are shown for this range in the legend, and the gain for the data overall is plotted (the solid line). The dashed line represents unity.

interpreted, their data (which are fairly linear out to 50° of azimuth) had a gain of 1.33 for eccentricities of 40° or less. These data are plotted in Figure 12.

Haun et al. (2005) have argued that verbal estimates of azimuthal direction from memory are biased away from categorical boundaries (including 90° eccentricity), and it is possible that the boundary effects observed by Fortenbaugh et al. (2012), when visible outer boundaries were present, were of a similar origin. When Fortenbaugh et al. imposed a visible outer boundary (or the body itself did—such as the nose does for nasal monocular eccentricity), they found relatively more evidence of (relative) expansion away from the outer boundary; but when the outer boundary was not a visible object, they primarily observed expansion away from fixation (which was visually marked in all conditions). This kind of pattern of results could be due to the kind of categorization effects proposed by Haun et al., but it could also occur as a result of participants changing reference frames when evaluating objects near to an outer (visible) boundary (see also Simmering, Spencer, & Schöner, 2006). In the study of Haun et al., visible boundaries were available both near straight ahead and near 90° as the edges of a circular curtain used as a backdrop that approximated a quadrant from the front to the left of the observer. Thus, reference-frame switching remains a possible explanation even for the data of Haun et al., consistent with expansion away from both straight ahead and from 90°. If we consider only data for eccentricities of 40° or less, however, the estimates collected by Haun et al. look similar to those observed by Fortenbaugh et al., as shown in Figure 12. Thus, although Haun et al. attributed the biases in their estimation data to category effects in memory, those biases seem to be identical to biases observed in perception.

There is, moreover, additional evidence of reference-frame switching in the azimuth estimation data of Higashiyama (1992). When Higashiyama had participants estimate the angular extents of horizontal intervals on the face of a building from different viewing distances, he observed strong linear angular exaggeration at the farthest viewing distance (30 m). The range of angles formed by the intervals at this distance was from 4° to 25°. For the same frontal intervals viewed from a distance of 3 m, most of the visual angles were closer to 90°, and among those greater than 45° (ranging from 63° to 78°), Higashiyama's data suggest linear expansion away from 90° though the gain is somewhat less. In this sense, Higazhiyama's azimuth data resemble those of Fortenbaugh et al. (2012) in showing a (weaker) tendency for repulsion from outer boundaries (i.e., 90°). It is interesting that no such reversed repulsion is evident in Higashiyama's elevation angle estimation data, and this may be because the egocentric vertical (90° elevation) is not a visually salient boundary, whereas the egocentric 90° (in azimuth) is a salient perceptual boundary. We have plotted all of the estimation data from Higashiyama's study for azimuthal eccentricities of 40° or less in Figure 12. The overall gain for these data is 1.25.

Philbeck et al. (2008) found that when using an exocentric pointer (e.g., a stick that rotated on a pivot in front of the observer) the perceived azimuthal direction of pointing was substantially misperceived—especially for directions that were behind the observer (see also Kelly, Loomis, & Beall, 2004; Koenderink, van Doorn, & Lappin, 2003). Philbeck et al. contrasted this with egocentric judgments of azimuthal direction

(in a 360° circle), allowing the observer to rotate fully. Verbal reports of azimuthal angle (sampled at 20° intervals in the frontal quadrants and 10° intervals behind) were fairly accurate when made egocentrically. Interestingly, however, when clock units rather than degrees were employed, the egocentric azimuthal estimation data of Philbeck et al. show angular expansion for eccentricities less than 45°. Both the clock face estimation data and the degrees estimation data of Philbeck et al. are also shown in Figure 12. The clock face data suggest a gain of about 1.18.

Philbeck et al. (2008) are fairly unique in observing no evidence of azimuthal bias with verbal degree estimates. This might be partly because they asked participants to use 10° as the finest grain of judgment for the verbal degree judgments, whereas they encouraged a 10-minute (5°) level of precision in their clock face estimation task. However, this is unlikely to be a sufficient account, based on control experiments they conducted. It is also possible, however, that the corners of their testing room provided an additional 45° reference frame that counteracted other reference frame effects in their study when degree estimation was used (45° is "1:30" in clock-face terms, which seems less likely to serve as a reference frame for clock-face estimates). Overall, a number of different paradigms (including the clock-face data of Philbeck et al.) seem to show systematic biases in perceived azimuthal direction even in near space, but the exact shape and nature of these biases is not always easy to interpret. We have emphasized the possibility that fairly linear expansion exists relative to a given reference frame, and that the relevant reference frame can shift depending on whether the requested angle is nearer to straight ahead or to some other salient reference (Fortenbaugh et al., 2012; Simmering et al., 2006).

In summary, Figure 12 shows the estimation data of all the studies discussed here for azimuthal eccentricities of 40° or less. There is some notable variability, but the general pattern suggests that the azimuthal angle tends to be exaggerated in the way our own data have suggested. Importantly, the magnitudes of azimuthal exaggeration observed by Fortenbaugh et al. (2012) in very near space and by Higashiyama (1992) in very far space are not terribly different. The overall gain for Figure 12 is 1.22 (1.28 if the degree-estimation data of Philbeck et al., 2008 are excluded), and a linear fit seems fairly reasonable out to 40°. Using the clock-face data of Philbeck et al., the gains implied by the other three studies for eccentricities up to 40°, and our own estimate of 1.26, suggests an overall azimuthal gain relative to straight-ahead of about 1.27, 95% CI [1.18, 1.34] across studies, though clearly there are factors that can affect the measured gain that are not understood at present.

As proposed by Durgin and Li (2011a; see also Higashiyama, 1992), perceptual expansion in spatial angular variables may be a functional biological coding choice. Some spatial angular variables provide important information regarding the spatial relationship between the observer and potential target(s) in space. For example, angular declination (the downward component of elevation) to a target on level ground tells you how far it is from you; azimuth direction helps you to figure out your heading direction relative to the target direction; optical slant tells you the orientation of a surface relative to your view of the surface, etc. Perceptual scale expansion in those angular variables (in the range where they are used) provides higher perceptual resolution (i.e., sensitivity). This may enhance the precision of control in relevant actions that are guided by feedback provided in terms of those perceptual angular variables. For the purpose of action control, accuracy of perception is not necessary because actions can (and will) be calibrated to stable distortions in perception (such as induced by the lenses in glasses, for example). It is therefore the precision of perceptual feedback that limits action calibration rather than the accuracy of perception. Thus it is the sensitivity or precision of perceptual coding that provides the basis for accuracy (or efficiency) in visually guided action.

Conclusion

We have previously proposed that many biases in the perception of spatial layout in locomotor space can be easily understood (and modeled) as errors in the perception of angular variables. In the present study, we further showed that visually perceived azimuth direction is also distorted. This finding has been supported by converging evidence concerning numeric angular estimation, verbal-distance estimation (i.e., Foley et al., 2004), and perceptual-extent matching. Our data suggest that systematic biases in the evaluation of both frontal and in-depth ground extents in locomotor space may be accounted for by the angular expansion hypothesis.

Keywords: angular expansion hypothesis, perceived visual direction, size perception, distance perception, horizontal vertical illusion

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Footnotes

[1] This follows the practice in aviation of using *elevation* and *azimuth* to indicate visual directions in the sagittal and the horizontal planes respectively. *Angular elevation* includes visual directions in the sagittal plane, both above and below eye level. "Angular declination" has become a standard term used to refer to the downward directions of angular elevation, but "declination" and "ascension" are also astronomical concepts that correspond roughly to latitude and longitude, whereas angular *elevation* and *azimuth* reference the terrestrial gravitational framework in which most human behavior takes place.

[2] Note that we do not regard matching measures such as manual actions (e.g., palm boards, pointing) as comparable measures of visual experience, because matching measures may often involve visual, haptic, or proprioceptive biases associated with the measure themselves. Inconsistencies between manual measures and perceptual reports may often be theoretically important (e.g., Philbeck et al., 2008), but it has also often turned out that manual measures are more susceptible to measurement artifacts (e.g., Li et al., 2013; Shaffer, McManama, Swank, Williams, & Durgin, 2014), than are other nonverbal perceptual measures.

[3] The temporal limit of the visual field is certainly greater than 90° (e.g., Rønne, 1915, cited in Traquair, 1938), but Fortenbaugh et al. (2012) normalized their data relative to the 90° limit of their measurements.

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Appendix. Deriving perceived azimuth direction from the extent-matching task

In Experiment 2, we used an egocentric extent-matching task as an implicit measure to assess perceived azimuth direction. Here, we show how the perceived azimuth direction was derived from the matching data.

The experiment setup used in Experiment 2 is shown in Figure 13 (assume the ground is flat). The physical viewing distance from the observer, O, to the frontal extent, BC, is D_1, and the corresponding perceived viewing distance is D_1'. The egocentric distance from the observer to experimenter A is D_2, and the corresponding perceived egocentric distance is D_2'. The physical size of the frontal extent is L, and the corresponding perceived size is L'. The physical azimuth angle subtended by the frontal extent is φ, and the corresponding perceived azimuth angle is φ'.

According to the second assumption of the angular expansion hypothesis (i.e., Laws of Euclidean geometry can still be applied to the perceived variables), the perceived size of the frontal extent, L', can be determined by the perceived azimuth angle, φ', and the perceived viewing distance to the frontal extent, D_1'.

$$L' = D_1' \tan(\varphi')$$

Because the participant's task was to match the perceived size of the frontal extent to the perceived egocentric distance to Experimenter A, i.e.

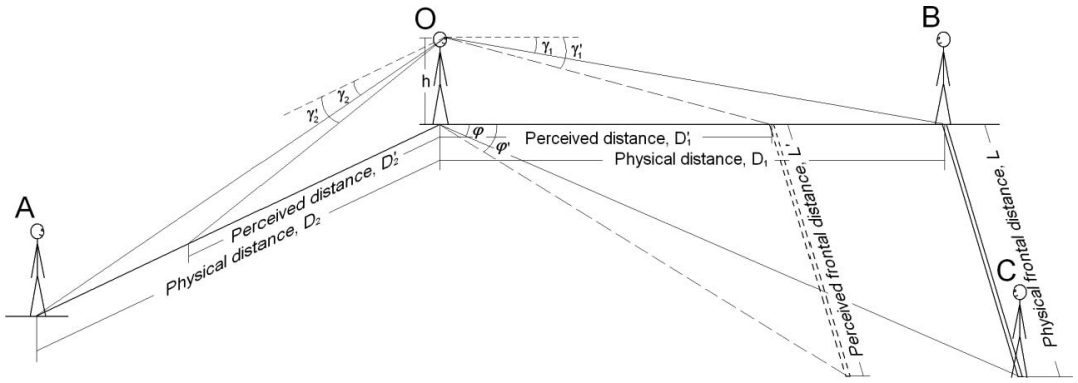

Figure 13. Diagram illustrating the geometry of the spatial variables in the experimental setup used in Experiment 2. Note that all the experimenters were on a level ground plane.

$$L' = D_2'$$

Replace L' with D_2' in the first equation, and we have

$$\tan(\varphi') = \frac{D_2'}{D_1'} \quad \text{(A1)}$$

According to the angular expansion hypothesis, the perceived egocentric distances (D_1' and D_2') are foreshortened due to the exaggeration in perceived angular declination (i.e., $\gamma' = 1.5\ \gamma$). The perceived egocentric distance is proportional to the physical egocentric distance when the distances are relatively large (because $\tan(\gamma) \approx \gamma$ for small angular elevations). Thus, in Equation A1, the ratio between the perceived distances, D_2'/D_1', can be approximated by the ratio of the physical distances, D_2/D_1. Then, the perceived azimuth direction, φ', can be determined by the ratio between D_2 and D_1, i.e.,

$$\varphi' = \tan^{-1}\left(\frac{D_2}{D_1}\right) \quad \text{(A2)}$$