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The perception of distances and spatial relationships in natural outdoor environments

J Farley Norman, Charles E Crabtree, Anna Marie Clayton, Hideko F Norman
Department of Psychology, Western Kentucky University, Bowling Green, KY 42101-3576, USA;
e-mail: Farley.Norman@wku.edu
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Abstract. The ability of observers to perceive distances and spatial relationships in outdoor environments was investigated in two experiments. In experiment 1, the observers adjusted triangular configurations to appear equilateral, while in experiment 2, they adjusted the depth of triangles to match their base width. The results of both experiments revealed that there are large individual differences in how observers perceive distances in outdoor settings. The observers' judgments were greatly affected by the particular task they were asked to perform. The observers who had shown no evidence of perceptual distortions in experiment 1 (with binocular vision) demonstrated large perceptual distortions in experiment 2 when the task was changed to match distances in depth to frontal distances perpendicular to the observers' line of sight. Considered as a whole, the results indicate that there is no single relationship between physical and perceived space that is consistent with observers' judgments of distances in ordinary outdoor contexts.

1 Introduction

Ever since the pioneering work of Weber (1834/1978, eg see pages 105 – 107) and Fechner (1860/1966, pages 176 – 197), psychophysicists have investigated the precision and accuracy of human observers' visual perceptions of distance. In many of these investigations, researchers have examined how observers perceive distances between pairs of environmental locations. These studies have revealed that observers apparently perceive distances in depth in a manner that is qualitatively different from how they perceive horizontal distances in a frontoparallel plane — in particular, it has been frequently found that distances in depth are perceptually compressed in relation to those that occur in the frontoparallel plane (eg see Beusmans 1998; Gilinsky 1951; Harway 1963; Loomis et al 1992; Loomis and Philbeck 1999; Norman et al 1996; Wagner 1985; Wu et al 2004). One can learn even more by studying how human observers perceive the spatial relationships between triplets of environmental points (eg Battro et al 1976; Blank 1958; Higashiyama 1981; Koenderink et al 2000). In an intriguing experiment conducted by Battro et al (pages 20 – 21), observers estimated the distances contained within large outdoor triangles. They concluded from their experiment (see their table 9) that for 15 m triangles (the length of the side of the triangle opposite the observer was 15 m), five of their ten observers' judgments were consistent with a hyperbolic geometry, while the remaining five observers' judgments were consistent with an elliptic geometry. In other words, none of the observers' estimates was consistent with ordinary Euclidean geometry — all of the observers perceived spatial relationships that indicated that their visual space was curved, either analogous to the surface of a horse's saddle (hyperbolic geometry) or to the surface of a sphere (elliptic geometry). These findings are remarkable and thought-provoking. However interesting the basic finding, it is impossible to learn anything more about Battro et al's results, because no actual data concerning this experiment were ever published in the 1976 article. All of the ten observers in the 15 m condition ostensibly exhibited significant perceptual distortions, but we do not know the precise nature or the magnitude of the distortions that were obtained. Were they large in magnitude? Were they small, but statistically significant?

The finding of individual differences is definitely interesting, but how large were these individual differences? How different were the judgments of the 'elliptic' and 'hyperbolic' observers? One of the primary purposes of the current experiments was to resolve these uncertainties by collecting new data regarding observers' abilities to perceive spatial relationships in outdoor settings. Important secondary purposes were to evaluate observers' perceptions of smaller spatial arrangements (the smallest triangles studied by Battro et al were 15 m across) and to compare observers' judgments with and without binocular vision. Previous experiments in outdoor environments were carried out only with binocular viewing—would the findings be different if the observers judged the spatial relationships monocularly?

2 Experiment 1

2.1 *Method*

2.1.1 *Apparatus and stimulus displays.* The endpoints of the spatial intervals to be judged (ie the vertices of the triangles) were marked by PVC plastic poles (1.56 m tall × 2.7 cm diameter). At the top of each pole was a spherical blue 'target' (5.6 cm in diameter). The configuration of poles was viewed by the observers outdoors in an open grassy field (see figure 1).

2.1.2 *Procedure.* On each trial, the observers' task was to create what appeared to be an equilateral triangle in depth. The observer was located at one vertex of the triangle. Another vertex was defined by a stationary pole that was located either 2 m (small

Figure 1. A photograph of the grassy field where the experiments were conducted. In this view, the observer (on the left, wearing a white shirt) is adjusting the triangular configuration to appear equilateral. The 'fixed' pole, located at a 15 m distance from the observer, is near the center of the image. The experimenter (near the right edge of the image, wearing a dark shirt), is moving the position of the 'adjustable' pole (ie the third vertex of the triangle) according to the directions supplied by the observer.

triangles) or 15 m (large triangles) from the observer in a random direction in the left part of the observer's visual field. At the beginning of each trial, an experimenter with a second pole (to define the third vertex of the triangle) stood next to the observer. The observer then adjusted the triangle to appear equilateral (ie make the distances or lengths of all three sides appear to be equal) by directing the experimenter where to place the adjustable pole. The observer was instructed to attend to the spherical 'targets' that were located approximately at eye height. The observer could take as much time as he or she needed to adjust the shape of the triangle to apparent equilaterality. Whenever an observer was contemplating the spatial arrangement and was not actively adjusting the movable pole, the experimenter moved away from the movable pole, thus allowing the observer to view the stimulus configuration by itself. This task was apparently first used in 1952; in a footnote, Blank (1958, page 914) describes the use of this task to investigate the curvature of perceived space and refers to "unpublished results at the Knapp Laboratory (1952)". This task was later used by Higashiyama (1981) to investigate the nature of perceived space in dark laboratory environments (Higashiyama's observers viewed two small points of light in total darkness). Our observers made their judgments using both binocular and monocular vision, creating a total of four experimental conditions [2 sizes of outdoor triangles (2 m and 15 m) × 2 viewing conditions (monocular versus binocular)]. Each of the observers in our experiment made 5 judgments within each of four experimental sessions (ie adjusted five triangles to apparent equilaterality). Each session was devoted to one of the four experimental conditions and lasted approximately 1 to 1.5 h; therefore, each observer made a total of 20 judgments across four experimental sessions lasting 4 to 6 h. The experimental sessions were run on separate days. For each size triangle (2 m or 15 m), half of the observers performed binocular judgments first, while the remaining observers performed monocular judgments first. Within each session, the observer was placed in a new random position at the beginning of each trial (also facing in a new random direction). The stationary pole was also placed in a new random position (at either a 2 m or a 15 m distance). This randomization was performed in order to ensure that on repeated trials the observers could not use any potential landmarks to aid their judgments (ie they could not replicate their previous adjustment by placing the adjustable pole at the same location as before).

2.1.3 *Observers.* There were a total of six observers, who were either students or members of the faculty at Western Kentucky University. Two of the observers were naive (JGD and MSH), and were unaware of the purposes of the experiment. The remaining four observers were the co-authors. All observers had normal or corrected-to-normal visual acuity.

2.2 *Results and discussion*

The observers' individual results are shown in figures 2a and 2b for the large and small triangles, respectively. If the observers had accurately adjusted each triangle to be equilateral (ie all side lengths equal to each other), the angle measured at the observers' vertex would have been 60°. One-sample t-tests were performed to check whether the observers' adjusted vertex angles deviated from what would have been expected from ordinary Euclidean geometry. It is readily apparent that the judgments of the observers were often inconsistent with Euclidean geometry and their vertex angles were significantly greater or smaller than 60°. The entries in tables 1 (large triangles) and 2 (small triangles) indicate those conditions (marked by asterisks) where the observers' judgments deviated significantly from Euclidean geometry.

In the 15 m condition (figure 2a), the vertex angles of three of the observers (AMC, CEC, and JGD) deviated from veridicality by almost 7° (ie the mean adjusted angle was 53.1°). According to Blank (1958), these observers' judgments are consistent

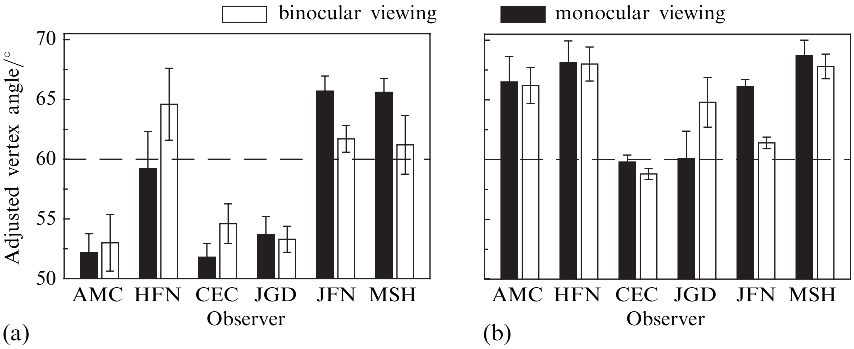

Figure 2. Individual results for (a) the 15 m conditions and (b) the 2 m conditions of experiment 1 for the six observers. If the observers' judgments had been accurate (ie if the observers had accurately adjusted the triangle to be equilateral), the angles measured at the observer's vertex would be 60° (indicated by the dashed line). The error bars indicate ±1 SE.

Table 1. 15 m triangles. Conditions where the observers' judgments deviated significantly from Euclidean geometry are marked by asterisks. This applies also to tables 2 and 3.

Observer	Monocular judgments		Binocular judgments	
	t	p	t	p
AMC	-4.993^*	0.008	-2.958^*	0.042
HFN	-0.256	> 0.05	1.528	> 0.05
CEC	-7.084^*	0.002	-3.250^*	0.031
JGD	-4.163^*	0.014	-6.142^*	0.004
JFN	4.520^*	0.011	1.527	> 0.05
MSH	4.802^*	0.009	0.489	> 0.05

Table 2. 2 m triangles.

Observer	Monocular judgments		Binocular judgments	
	t	p	t	p
AMC	3.047^*	0.038	4.143^*	0.014
HFN	4.419^*	0.012	5.622^*	0.005
CEC	-0.343	> 0.05	-2.588	> 0.05
JGD	0.044	> 0.05	2.304	> 0.05
JFN	10.167^*	< 0.001	2.888^*	0.045
MSH	6.692^*	0.003	7.558^*	0.002

with a hyperbolic geometry,(1) indicating that their three-dimensional (3-D) visual space is curved (a 2-D hyperbolic surface is curved like a horse's saddle). The judgments of the remaining three observers (HFN, JFN, and MSH) were consistent with Euclidean geometry in at least one viewing condition. The pattern of results obtained for observers JFN and MSH was especially interesting. The judgments of these observers were consistent with Euclidean geometry with binocular viewing, but became consistent with an elliptic geometry when they performed the task monocularly (a 2-D elliptic surface is curved like a hemisphere). In one sense, it is perhaps not surprising that these observers' judgments were more accurate (ie veridical) in the binocular condition; in this condition, more optical information, such as binocular disparity, was available

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(1) In making this conclusion, Blank (1958, page 912) assumed that binocular visual space was a "Riemannian space of constant Gaussian curvature". Observer vertex angles less than 60° could also occur because of other perceptual distortions, such as an affine compressive distortion in depth.

to support the observers' perceptions of distance. Given more thought, however, this result is somewhat perplexing. Notice that, while performing the task, the observer is required to judge the magnitudes of the egocentric depth intervals between himself or herself and the two targets, and equate those distances in depth to the frontal distance between the two targets. Estimating the egocentric distance to each of the targets cannot be performed with the use of conventional binocular disparity (an observer utilizes conventional binocular disparity when an observer estimates the distance between a *pair* of environmental 'targets'—in this task, the observers were judging the absolute egocentric distance to a single target in depth). Convergence could potentially be used to estimate such egocentric distances, but convergence is generally considered to be an unreliable cue for distances beyond 2 m (eg see Gulick and Lawson 1976, page 251). One possible explanation for these observers' (JFN and MSH) more accurate binocular judgments at such far distances involves the sequential-surface-integration process (SSIP; see He et al 2004). In this process, accurate judgments are possible at far distances, because the relatively accurate information about depth intervals obtained at near distances from binocular disparity is then propagated along the ground surface (which is itself defined by such information as texture gradients).

The results for the smaller triangles (2 m condition) are shown in figure 2b. From a comparison of figures 2a and 2b, one can see that the observers' adjusted vertex angles for the 2 m triangles are generally much higher than those obtained for the larger 15 m triangles (this was true for five out of the six observers; JFN was the only observer whose judgments were unaffected by the change in size of the outdoor triangles). This effect of triangle size is summarized in figure 3. As a group, the observers' judgments were more consistent with a hyperbolic geometry for the larger triangles, and were more consistent with an elliptic geometry for the smaller triangles. This main effect of triangle size was significant, as shown by the results of a two-way within-subjects analysis of variance ($F_{1,5} = 12.8$, $p = 0.016$). This finding agrees with that of Koenderink et al (2000, see their figures 4 and 6). One can also see from an inspection of figure 3 that, overall, the observers' binocular judgments were not more accurate than their monocular judgments [although this was not true for two of the individual observers, JFN and MSH, as was indicated previously ($F_{1,5} = 0.03$, $p > 0.05$)].

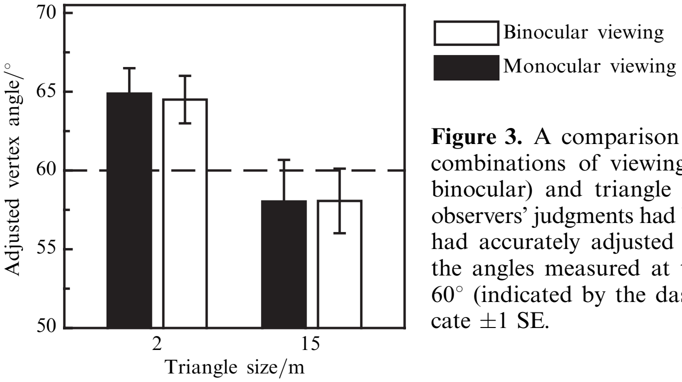
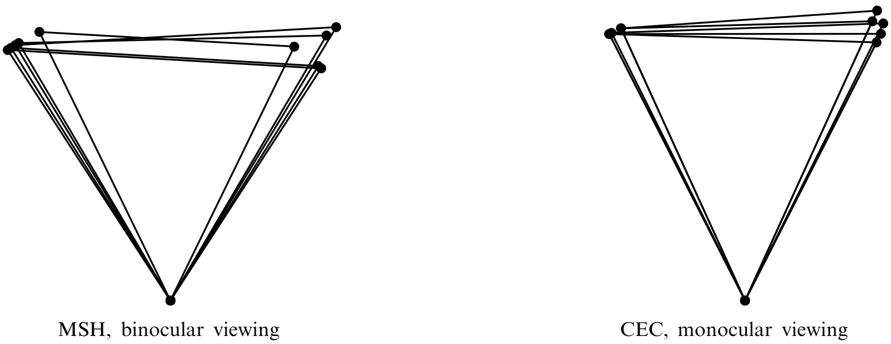


Figure 3. A comparison of the group means for the 4 combinations of viewing condition (monocular versus binocular) and triangle size (2 m versus 15 m). If the observers' judgments had been accurate (ie if the observers had accurately adjusted the triangle to be equilateral), the angles measured at the observer's vertex would be 60° (indicated by the dashed line). The error bars indicate ±1 SE.

It is clear from an inspection of figures 2a and 2b that the observers' judgments were often inaccurate. But the observers were reliable and consistent in their repeated judgments over time. The average of the observers' reliabilities (we measured reliability as the standard deviation of the observers' judgments divided by their mean) was 5.7%, and was identical for monocular and binocular viewing ($F_{1,5} = 0.008$, $p > 0.05$). The observers' reliabilities were also unaffected by the size of the outdoor triangles ($F_{1,5} = 4.7$, $p > 0.05$). The observers' individual reliabilities ranged from 1.8% to 11.8%.

These reliabilities are comparable to those previously obtained for indoor judgments of distance (eg see Norman et al 1996, 2000, 2004). Figure 4 graphically depicts the adjusted triangles produced by observers MSH (binocular viewing, 15 m) and CEC (monocular viewing, 15 m). One can therefore see the magnitude of the variability that typically existed across trials for the same conditions. It is important to remember that, while the individual triangles are shown overlapping in this figure (to illustrate the observers' variability), when the experiment was performed each triangle was presented outdoors in a different, randomly determined location and orientation.


MSH, binocular viewing

CEC, monocular viewing

Figure 4. Individual trial results of experiment 1 for observers MSH (binocular 15 m condition) and CEC (monocular 15 m condition). The five adjusted triangles for each observer have been superimposed to illustrate the magnitude of the variability of the observers' responses across repeated trials. The vertices of each of the five triangles have been connected by straight lines only to indicate which vertices 'belong together'.

3 Experiment 2

The first experiment demonstrated that there are substantial individual differences in how human observers perceive 3-D spatial relationships in outdoor environments. In the 15 m monocular condition, the judgments of three observers (AMC, CEC, and JGD) were consistent with hyperbolic geometry, those of one observer (HFN) were consistent with Euclidean geometry, and those of the two remaining observers (JFN and MSH) were consistent with elliptic geometry. The results were somewhat different for binocular viewing: the binocular visual space of half of the observers (AMC, CEC, and JGD) was hyperbolic, while that of the remaining half (HFN, JFN, and MSH) was Euclidean. When the triangle size was reduced from 15 m to 2 m, the observers' vertex angles significantly increased by an average of 6.64°, but the individual differences persisted. For example, judgments of four of the observers (AMC, HFN, JFN, and MSH) were consistent with elliptic geometry with monocular viewing, while those of the remaining two observers (CEC and JGD) were Euclidean.

Loomis et al (1992; also see related findings by Beusmans 1998; Gilinsky 1951; Harway 1963; Loomis and Philbeck 1999; Norman et al 1996; Wagner 1985; Wu et al 2004) showed that when observers performed a different task (also involving outdoor judgments of distance among three environmental locations), they consistently demonstrated a different pattern of perceptual distortion, an affine compression in depth. Many of the judgments of our observers in experiment 1 were Euclidean in nature (eg those of HFN, JFN, and MSH in the 15 m condition and those of CEC, JGD, and JFN in the 2 m condition), and thus were not consistent with this type of perceptual distortion. Would our observers, in the same outdoor environment and with the same apparatus as used in experiment 1, obtain the same compressive distortion as that found by Loomis et al if they adopted their task? Or would the change in task be irrelevant? Experiment 2 was designed to answer these questions.

3.1 *Method*

3.1.1 *Apparatus and stimulus displays.* The apparatus and stimulus displays were identical to those used in experiment 1. The stimuli were viewed in the same outdoor grassy field that was used in the earlier experiment.

3.1.2 *Procedure.* Two poles were placed 4 m apart, perpendicular to the observers' line of sight. A third pole was moved by an experimenter along the observers' line of sight, and on each trial was initially located midway between the first two poles. This configuration of three poles was viewed by each observer from a distance of 8 m. On any given trial, an experimenter moved the adjustable pole away from its initial location along the observers' line of sight until the distance in depth (from the adjustable pole to the plane formed by the two fixed poles) appeared to be equal to the distance between the two fixed poles. Note that, as in experiment 1, the observers were required to adjust a triangle in depth to a specific shape—one in which the height of the triangle (distance in depth) appeared to equal the base of the triangle (distance in width, in a direction perpendicular to the depth dimension). Each observer performed this adjustment task five times in a single experimental session. All judgments were made binocularly. Each experimental session took about 1 h to complete. On every trial, the observer was placed at a new randomly determined location and faced in a new random orientation (ie the two fixed poles were moved to a new position and orientation) to prevent the possibility of the observers using any potential landmarks to assist their judgments.

3.1.3 *Observers.* All of the six observers had previously participated in experiment 1. Observers JGD and MSH were once again naive with regard to the purposes of the experiment. All observers had normal or corrected-to-normal visual acuity.

3.2 *Results and discussion*

The observers' individual results are shown in figure 5. The ordinate shows the amount of depth needed by the observers to apparently match the width (ie the base of the triangle, 4 m). The data are plotted as ratios of adjusted depth to width: therefore, accurate performance would be indicated by a ratio of 1.0. It is readily apparent from an inspection of figure 5 that the judgments of the observers were not accurate. All of the observers' judgments were inconsistent (see table 3, significant deviations marked by asterisks) with Euclidean geometry and indicated either significant perceptual compression (five observers: HFN, JFN, MSH, CEC, and AMC) or perceptual expansion in depth (one observer: JGD). The majority of the observers exhibited perceptual compression, and they needed anywhere from 11% to 118% more depth for those distances to appear equal to the standard 4 m frontal distance. The average perceptual compression for the five observers was 36.3%; this means that, for those observers, a depth interval of 6.28 m appeared equivalent, on average, to a frontal interval of 4 m.

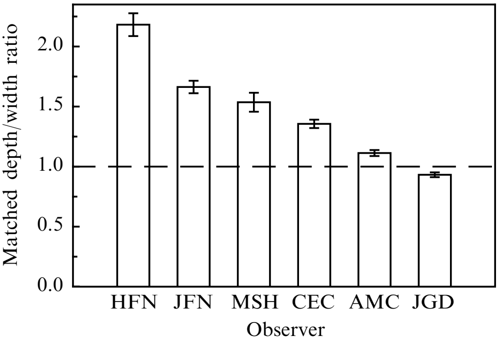


Figure 5. Individual results of experiment 2 for the six observers. If the observers had been able to accurately match distances in depth with perpendicular frontal distances, then the depth-to-width ratios would equal 1.0. The error bars indicate ±1 SE.

Table 3. Match depth to width.

Observer	Binocular judgments	
	t	p
AMC	4.508^*	0.011
HFN	12.436^*	< 0.001
CEC	10.219^*	< 0.001
JGD	-3.397^*	0.027
JFN	12.728^*	< 0.001
MSH	6.743^*	0.003

The average perceptual compression for those observers whose judgments were consistent with Euclidean geometry in figure 2a (HFN, JFN, and MSH) was an even higher 44.2%. It is interesting that these observers exhibited such large perceptual distortions in this experiment, given that their binocular judgments were not significantly distorted for the large triangles in experiment 1. Once again, the observers were reliable in their repeated judgments over time, even if they were not accurate: the observers' average reliabilities were 7.3% and were not statistically different from those obtained for the binocular, large triangle condition of experiment 1 ($t_5 = 0.1$, $p > 0.05$).

The wide range of individual differences obtained in this experiment for outdoor judgments of 3-D spatial relationships (figure 5) strongly resembles the individual differences often found for human judgments of the depth and 3-D shape of objects defined by binocular disparity, image shading, motion, etc (eg see figures 4, 8, and 11 of Todd and Norman 2003; also see Koenderink et al 1994, 1995; Norman et al 2000, 2004; Todd et al 1997).

4 General discussion

Previous researchers have found visual space to be curved (eg Battro et al 1976; Koenderink et al 2000), while others have found visual space to be distorted in an affine manner (ie compressive distortions in depth—Beusmans 1998; Gilinsky 1951; Harway 1963; Loomis et al 1992; Loomis and Philbeck 1999; Norman et al 1996; Wagner 1985; Wu et al 2004). The observers in most of these investigations (ie those participating in the same experiment) have exhibited the same kind of perceptual distortion. For example, in the study of Koenderink et al, all of their three observers' judgments were consistent with an elliptic geometry in near visual space (within 2 to 3 m), but were consistent with a hyperbolic geometry in far visual space (14 to 20 m). The results of our experiment 1 revealed the existence of significant qualitative individual differences—for example, under the same binocular 15 m conditions, the judgments of observers AMC, CEC, and JGD (mean observer vertex angles were less than 60° at apparent triangle equilaterality) were qualitatively different from those of observers HFN, JFN, and MSH, whose judgments were consistent with traditional Euclidean geometry (mean observer vertex angles were not significantly different from 60°). Furthermore, when the viewing of the triangles was restricted to monocular vision, the judgments of some, but not all, observers (JFN and MSH) changed to reveal that their monocular visual space was elliptic. The presence of these significant individual differences would appear to support the conclusions of Battro et al (1976), who also apparently found (but did not report any quantitative data for their triangle experiment) significant individual differences. Our results were obtained by requiring observers to estimate and equate distances in different directions. The observers in the Koenderink et al experiment performed an exocentric pointing task. It would be important for more observers to perform the task of Koenderink et al—would individual differences emerge if more observers participated in the exocentric pointing task? In our experiment 1, if we had used only three observers [either (i) CEC, AMC, and JGD, or (ii) HFN, JFN, and MSH in the binocular 15 m condition], we would not have found individual differences either.

A comparison between the results of experiments 1 and 2 would appear to indicate that the nature of the specific task employed determines the perceptual outcome. In experiment 1, the far binocular space of observers HFN, JFN, and MSH was consistent with traditional Euclidean geometry (see figure 2a). In experiment 2, it was found for these same observers (in the same grassy environment) that their perceived space was characterized by a large affine compression along the depth axis (ie the same results as found by Loomis et al 1992). On the one hand, it is perhaps not surprising that the task matters. On the other hand, this qualitative difference between experiments is quite puzzling. What does it mean that these observers' binocular far visual space is sometimes Euclidean and sometimes compressed in depth? In a sense, both of these results can occur at the same time, since both of these patterns were obtained while the observers were estimating distances within the same outdoor area of space! Whether a Euclidean or an affine compressed visual space was obtained depended not upon any characteristics of the visual stimuli, but upon the specific task employed by the observer. If the observer was asked to equate a frontal distance with a distance aligned along the depth axis, then an affine compression in depth was obtained. If the same observer was asked to adjust an outdoor large triangle to apparent equilaterality, then his or her judgments were not distorted and became consistent with Euclidean geometry.

The finding that the nature of perceived space depends upon the task used to measure it has troubling implications. For example, how can we answer the question "what is the real nature of visual space?" There appears to be no single relationship between physical and perceived space that can account for all of the observed findings. Beusmans (1998), Gilinsky (1951), Harway (1963), Loomis et al (1992), Loomis and Philbeck (1999), Norman et al (1996), Wagner (1985), and Wu et al (2004) have all found visual space to be an affine compressed distortion of physical space, such that distances in depth appear shorter than they really are. In contrast, Norman et al (2000, 2004) have found that distances along a curved surface in depth frequently appear longer than they really are. With other tasks, other investigators (such as Koenderink et al 2000) have found visual space to be curved and not subject to affine compressions or expansions. The findings of the current set of experiments, taken together with those of the rest of the recent literature, would appear to conclusively indicate that there is no consistent relationship between physical and perceived visual space, even for a single observer in a given environment. Foley et al (2004) have recently concluded that "although the perception of location and the perception of extent are related, they are not related by Euclidean geometry, nor by any metric geometry". We tend to agree. Our human perceptions of distance and spatial relationships are distorted and often inaccurate; furthermore, these distortions and inaccuracies themselves change with context and the nature of the perceptual task employed. This extreme failure of 'length' or 'distance' constancy across contexts is probably why we humans depend so much upon rulers, yard, or meter sticks, or other measurement aids—we simply cannot perceive distances accurately even in the most full-cue environments. Our results from the 2 m condition of experiment 1 are especially provocative (see figure 2b; also see figure 10 of Norman et al 1996; and Norman et al 2000, 2004); human observers apparently do not perceive distances accurately in any condition, even within 2 m in near visual space.

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