Psychological Review
2007, Vol. 114, No. 2, 441–454

0033-295X/07/$12.00 DOI: 10.1037/0033-295X.114.2.441

THEORETICAL NOTES

A Distance Judgment Function Based on Space Perception Mechanisms: Revisiting Gilinsky's (1951) Equation

Teng Leng Ooi
Pennsylvania College of Optometry

Zijiang J. He
University of Louisville

In her seminal article in *Psychological Review*, A. S. Gilinsky (1951) successfully described the relationship between physical distance (D) and perceived distance (d) with the equation $d = DA/(A + D)$, where A = constant. To understand its theoretical underpinning, the authors of the current article capitalized on space perception mechanisms based on the ground surface to derive the distance equation $d = H\cos\alpha/\sin(\alpha + \eta)$, where H is the observer's eye height, α is the angular declination below the horizon, and η is the slant error in representing the ground surface. Their equation predicts that (a) perceived distance is affected by the slant error in representing the ground surface; (b) when the slant error is small, the ground-based equation takes the same form as Gilinsky's equation; and (c) the parameter A in Gilinsky's equation represents the ratio of the observer's eye height to the sine of the slant error. These predictions were empirically confirmed, thus bestowing a theoretical foundation on Gilinsky's equation.

Keywords: distance judgment, eye height, ground surface, space perception, successive equal-appearing intervals task

The ability to perceive space and be aware of one's surrounding spatial layout in the intermediate distance range (2–25 m) is vital for guiding and directing actions such as navigating, aiming, and throwing. Given its importance, researchers have used various approaches to understand how the perceptual space is constructed from the spatial information in the physical world. One approach is to derive a quantitative formulation that relates the judged distance (d) to the physical distance (D), $d = \mathrm{f}(D)$ (e.g., Baird & Biersdorf, 1967; Beusman, 1998; Da Silva, 1985; Eby & Loomis, 1987; Foley, 1980; Foley, Ribeiro, & Da Silva, 2004; Gilinsky, 1951; Gogel, 1977; Loomis, Da Silva, Fujita, & Fukusima, 1992; Loomis, Da Silva, Philbeck, & Fukusima, 1996; Luneburg, 1947; Ooi, Wu, & He, 2001; Toye, 1986; Wagner, 1985; B. Wu, Ooi, & He, 2004).

Gilinsky (1951) was one of the first to use this approach to investigate space perception in the intermediate distance range, and her findings have remained an intrigue to researchers in space perception. She used the procedure involving successive equal-appearing intervals to derive the relationship between perceived and physical distances. In her experiment, she instructed the observer to match the depth interval between a horizontal rod marker and a pointer stick on the ground to a remembered perceptual length of 1 ft (0.30 m). Multiple trials were conducted at various distances, successively, from the near to intermediate distance range (80 ft, or 24.38 m). Gilinsky found that the observer required a successively longer length between the marker and pointer stick to match the remembered perceptual length of 1 ft as the viewing distance increased. This indicates an underestimation of the depth or distance (foreshortening) on the ground surface over the spatial range tested (<80 ft, or 24.38 m). In modeling her data, Gilinsky found that the data could be fitted remarkably well by the following equation:

$$d = \frac{DA}{D + A}. \tag{1}$$

In the equation above, d and D denote, respectively, the judged and physical distances on the ground surface. Parameter A is a numeric, distance-scaling value that is unique for the individual observer. The value of parameter A for the individual observer depends on the available depth cues in the physical space (Gilinsky, 1951). Furthermore, the Gilinsky equation suggests that when the physical distance D is set at infinity, the perceived distance d will be equivalent to A. Accordingly, the parameter A can be considered the asymptotic limit of the perceived distance.

A theoretical advantage of quantifying perceptual performances in terms of the function $\mathrm{f}(D)$ is twofold. It both informs about how physical distance is scaled by the visual system and reflects the characteristics of the perceptual mechanisms underlying distance judgments. Thus, one should be able to relate the function $\mathrm{f}(D)$, such as the equation above by Gilinsky (1951; Equation 1), to the mechanisms that mediate space perception in the intermediate distance range.

A number of recent investigations have found that judged distance is influenced by the ground-surface information (Bian,

This research was supported by National Institutes of Health Grant R01-EY014821 to Zijiang J. He and Teng Leng Ooi. A preliminary version of this work was presented at the May 2004 meeting of the Vision Sciences Society in Sarasota, Florida. We thank Yong Su for collecting part of the data in Experiment 1. We are also grateful to Myron Braunstein, Jack Loomis, and Harold Sedgwick for their thoughtful comments on a draft of this article.

Correspondence concerning this article should be addressed to Teng Leng Ooi, Department of Basic Sciences, Pennsylvania College of Optometry, 8360 Old York Road, Elkins Park, PA 19027, or to Zijiang J. He, Department of Psychological and Brain Sciences, University of Louisville, Louisville, KY 40292. E-mail: tlooi@pco.edu or zjhe@louisville.edu

Braunstein, & Andersen, 2005; Feria, Braunstein, & Andersen, 2003; He & Ooi, 2000; He, Wu, Ooi, Yarbrough, & Wu, 2004; Madison, Thompson, Kersten, Shirley, & Smits, 2001; Meng & Sedgwick, 2001, 2002; Ni, Braunstein, & Andersen, 2004; Ooi et al., 2001; Ooi, Wu, & He, 2006; Philbeck & Loomis, 1997; Sinai, Ooi, & He, 1998; B. Wu et al., 2004), consistent with the view espoused in the ground theory of space perception (Gibson, 1950, 1979; Sedgwick, 1986). For example, judged distance of a target from the observer is accurate on a homogeneous ground surface and is inaccurate when a gap, an obstacle, or a texture boundary interrupts the ground surface. In fact, the eminence of the ground surface in space perception has led to the notion that the visual system operates by constructing a ground-surface representation for use as a reference frame. Once formed, the ground reference frame, in conjunction with the angular declination of the object (Ooi et al, 2001, 2006; Philbeck & Loomis, 1997), is used to locate the object in the intermediate distance range. Even when the object has no direct contact with the ground surface, the visual system can use a variety of depth information (e.g., binocular disparity, motion parallax, cast shadow, and nested contact information) in conjunction with the ground surface to determine the object location (Madison, Thompson, Kersten, Shirley, & Smits, 2001; Meng & Sedgwick, 2001, 2002; Ni et al., 2004; Ooi & He, 2006; Sedgwick, 1989; J. Wu et al., 2004).

On the basis of the recent findings, one can propose that $d = f(D)$ in the intermediate distance range should reflect the space perception mechanisms linked to the ground surface. To substantiate this proposal, in our study, we focus on Gilinsky's (1951) equation (Equation 1) because it provides a remarkable fit to the empirical data. Our specific goal is to investigate whether the underestimation of distance described by Gilinsky's equation could be related to the error in representing the ground surface. This investigation also allows us to attach a new significance to the parameter A in Gilinsky's equation.

A Theoretical Analysis Based on the Geometry of the Ground-Surface Representation

We begin with the following theoretical analysis based on the geometrical relationship between the perceived distance on the ground and the representation of the ground surface. For an object located on a horizontal ground surface (Figure 1a), the visual system can derive its egocentric distance on the ground surface (D) using the trigonometric relationship

$$D = \frac{H}{\tan \alpha}. \tag{2}$$

In Equation 2, H and α denote the eye height and the angular declination below the horizon, respectively. (It should be pointed out here that we are not proposing that the visual system directly follows the operational procedures specified by the mathematical equation above to derive distance. Rather, we believe that the visual system is likely to construct a perceptual space in which the geometrical relationship determines the object distance. As such, our analysis in this article is formulated to facilitate the understanding of the information [parameters] used for computing the perceptual space that leads to perceived distance.) The potential of the trigonometric strategy to derive an accurate egocentric distance depends on the visual system's ability to correctly represent the ground surface (i.e., defining a horizontal ground surface as horizontal instead of slanted), the angular declination of the object, and the eye height. Conversely, when the visual system makes errors in judging egocentric distance, one should be able to identify the sources of errors associated with these three factors. We have applied this analysis to the classical Gilinsky (1951) study that showed an underestimation of the observer's distance from an object on the ground.

We hypothesize that of the three factors, the ground surface (error in representation) is perhaps the main factor in the distance underestimation finding of Gilinsky's (1951) study. There are reasons to believe that the other two factors, eye height and angular declination, are less likely to have significant representation errors. First, this is because in the light environment, the visual system can accurately obtain the eye height using the reliable near depth cues (e.g., binocular disparity, motion perspective) on the ground surface. Second, the visual system could store the eye-height information in memory because an individual's eye height remains more or less constant through adulthood. Third, as for the angular declination factor, the visual system can use the eye level as its

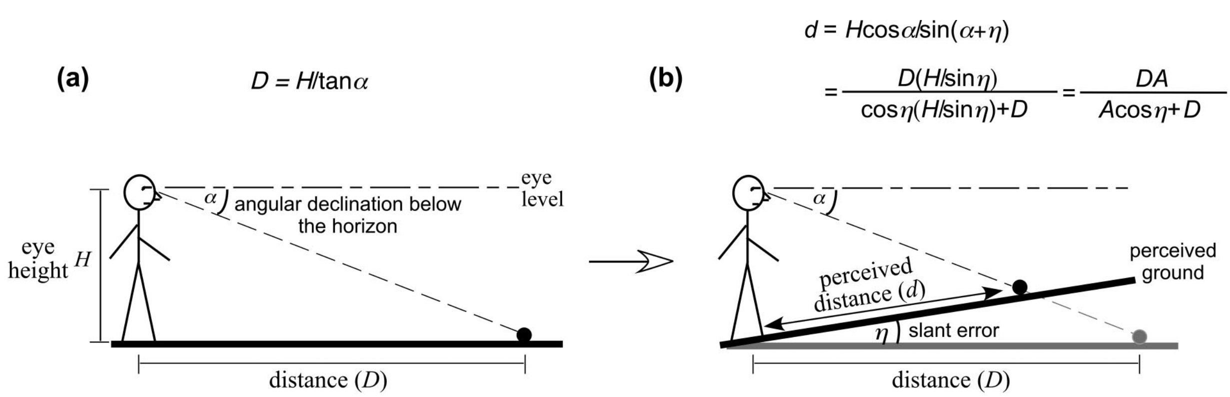

Figure 1. a: The target distance (D) on a horizontal ground surface can be determined by the trigonometric relationship, $D = H/\tan\alpha$. b: The horizontal ground is represented by the visual system as a slant surface with a geographical slant error (η). Accordingly, the perceived target distance (d) is described by the trigonometric relationship $d = DA/(D + \cos\eta A)$, where A can be considered a distance-scaling factor.

reference. The amplitude of the gaze position from the eye level (reference) and the angular distance of the target's retinal image from the fovea determine the angular declination of a target. Arguably, if the visual system can accurately register the gaze position and the angular distance of the target's retinal image, the accuracy of the angular declination would depend mainly on the accuracy of the eye level. Supporting this argument, a number of psychophysical studies have demonstrated that the observer is sufficiently accurate in judging the visually perceived eye level in the natural visual environment (e.g., MacDougall, 1903). In a dark environment, the visually perceived eye level is reasonably reliable ($<1°$), even after accounting for some systematic deviations from the true eye level (Matin & Li, 1994; Ooi et al., 2001, 2006; Stoper & Cohen, 1986; J. Wu, Ooi, & He, 2005). Moreover, in an otherwise dark room, observers judge a dimly lit target as if it is located on an implicit slant surface (the intrinsic bias of the visual system) with its angular declination (i.e., the egocentric direction) remaining quite accurate (Ooi et al., 2001, 2006).

As for the representation of the ground surface, recent investigations from our laboratory suggest that the visual system relies on a sequential surface integration process (SSIP) to construct the ground representation (He et al., 2004; Sinai et al., 1998; B. Wu et al., 2004). According to the SSIP hypothesis, the visual system begins by constructing the near ground-surface representation using the reliable near depth cues. It then uses the near ground-surface representation as a template to sequentially integrate the far surface patches using texture gradient information to form a global surface representation. The visual system, however, cannot obtain an accurate global representation of the ground surface when the viewing condition is not optimal for the SSIP. An inaccurate global surface representation leads to an error in judging distance on the ground surface (He et al., 2004; Sinai et al., 1998; B. Wu et al., 2004). (Examples of nonoptimal viewing conditions include when the visual system is devoid of the near ground-surface information, when a texture discontinuation exists on the ground surface, and when the texture gradient information on the ground is reduced.)

For example, Sinai et al. (1998) found that an observer standing on a concrete-texture surface underestimates the distance of a target on the far grass surface. According to the SSIP hypothesis, the SSIP can only form an accurate ground-surface representation from the near ground forward up to the texture boundary (where the concrete meets the grass). The presence of a texture discontinuation indicates to the visual system the end of the homogeneous surface, which terminates the integration process. Thus, beyond the texture boundary, the visual system (SSIP) has to begin constructing a new template surface for further integration. However, because the far surface is located beyond the effective range of the reliable near depth cues, the visual system can no longer form an accurate template surface. Consequently, the new template surface is more likely to be affected by the visual system's intrinsic bias that causes it to be represented as slanted with its far end upward (He et al., 2004; Ooi et al., 2001, 2006). This means that the far texture surface is represented as slanted upward and the target distance on the far ground surface is underestimated. This explanation is supported by other separate investigations from our laboratory in the real 3-D environment as well as in the virtual reality environment (B. Wu, He, & Ooi, 2002, in press-a; J. Wu, He, & Ooi, 2004, 2006).

B. Wu et al. (2002, in press-a) created a checkerboard-textured ground surface in a virtual reality environment. In one experiment, observers had to judge the target distance on a checkerboard surface with a texture boundary that was created with a relative phase shift between the far and near checkerboard-textured patterns (test condition). It was found that the observers underestimated the distance of a target that was located on the far checkerboard surface beyond the texture boundary, compared with the estimations of observers in the control condition with a homogeneous checkerboard-textured ground surface. This finding is similar to the observations made in the real 3-D environment (Sinai et al., 1998). Additionally, in a related experiment in the virtual environment, we asked the observers to adjust the slant of the far checkerboard surface so that it appeared coplanar with the horizontal near checkerboard surface. We found that the observers had to set the slant of the far surface downward ($-\eta$) to perceive both the near and the far surfaces as horizontal and coplanar. Thus, this finding supports the prediction of the SSIP hypothesis that the observer perceives the far checkerboard surface beyond the texture boundary as slanted upward ($+\eta$).

Another study from our laboratory (J. Wu et al., 2004, 2006) provided direct evidence for the prediction that in a nonoptimal viewing condition, the visual system represents the ground surface with an upward slant error and distance with a compression error. The nonoptimal condition was created by an array of parallel phosphorescent-element texture on the horizontal floor in an otherwise dark room to form the background surface. A phosphorescent L-shaped target was placed on this horizontal background. The observers were required to make three types of judgments of the L-shaped target. First, in the blind walking–gesturing task, they judged the target's egocentric location, which was underestimated. Of significance, the underestimation could be explained by the assumption that the target was represented on an implicit slant surface (i.e., the horizontal background was represented as slanted). The second experimental task measured the judged aspect ratio of the two limbs of the L-shaped target. We found that the sagittal limb of the L-shaped target was underestimated (foreshortened), which also supports the prediction that the L-shaped target was perceived as if it were located on an upward-slanting surface (Ooi et al., 2006; B. Wu et al., 2004). The third experimental task directly measured the perceived surface orientation of the L-shaped target by requiring observers to indicate with their hands the perceived slant of the L-shaped target. We found that the L-shaped target was judged as if it were slanted upward, despite being laid on the horizontal floor with the phosphorescent texture. Because both the target and the background were physically on the same horizontal plane, we can assume that the judged surface slant of the L-shaped target reflects the slant of the perceived background surface. Altogether, these three measurements reveal that with only an array of parallel phosphorescent-element texture on the horizontal floor in the dark (i.e., a nonoptimal condition), the ground surface is represented as slanted upward and distance is underestimated.

Revisiting the Gilinsky (1951) Equation

Studies have shown that when an observer has only a limited visual field of view of a target and its surrounding ground in the intermediate distance, he or she underestimates both the egocentric distance of the target and the length-in-depth of the target (Creem-Regehr, Willemsen, Gooch, & Thompson, 2005; Dolezal, 1982; Hagen, Jones, & Reed, 1978; Shah & Sedgwick, 2004; B. Wu et al., 2004). According to the SSIP hypothesis, this is because with the limited visual field of view, the visual system has no access to the near ground surface. And without reliable near depth information (Cutting & Vishton, 1995), the representation of the global ground surface is highly influenced by the visual system's intrinsic bias that has an upward slant error. Indeed, in the study by B. Wu et al. (2004), the underestimation error of the data can be explained by assuming the global ground surface representation has an error, with its far end slanted upward.

The task of judging distance with a limited field of view has a parallel with Gilinsky's (1951) successive equal-appearing intervals task. In the latter task, despite having a full view of the ground surface, the observer has a tendency to direct his or her attention to the target and its surrounding local ground surface rather than to the global ground surface (including the near ground surface). Thus, as explained in B. Wu et al. (2004), we hypothesize that the foreshortening in Gilinsky's task is in part attributable to the fact that the visual system fails to adequately sample the near ground-surface information, as the observer concentrates on the targets located on the more distant ground surface. The consequence is that the global representation of the horizontal ground surface is slanted upward (which we assume for now is largely planar with a constant surface slant error; see Figure 1b) and the distance representation on the ground is underestimated. From Figure 1b, we can also derive a quantitative relationship between the perceptual distance and physical distance on a horizontal ground surface, where

$$d = \frac{H \cos \alpha}{\sin(\alpha + \eta)}. \tag{3}$$

Because $D = H/\tan\alpha$ (Equation 2), we can substitute Equation 3 above as follows:

$$d = \frac{DH/\sin \eta}{H \cos \eta/\sin \eta + D}. \tag{4}$$

To simplify, we can further define $H/\sin\eta = A$. Thus Equation 4 can be rewritten as

$$d = \frac{DA}{A \cos \eta + D}. \tag{5}$$

Note that when η is very small, $\cos\eta$ will be close to unity, and Equation 5 takes the exact same form as Gilinsky's equation (Equation 1). Therefore, our analysis based on the ground-surface mechanisms provides a new meaning to the parameter A in Gilinsky's equation (Equation 1). Namely, parameter A defines the ratio of the eye height to the sine of the slant error in representing the ground surface.

According to our analysis above, parameter A will be affected by the observer's eye height. Because the eye height is the vertical distance from the eye to the ground surface of regard, in our first experiment, we manipulated the eye height in three conditions while observers performed the Gilinsky task (a successive equal-appearing intervals task to measure judged distance). These conditions involved having the observer stand on the ground (baseline H), sit on a chair (reduces H), and stand on a ledge (increases H). The data obtained in each condition are fitted by a curve representing Equation 4, and, if our hypothesis is correct, we expect that parameter A changes with the eye height. Our prediction echoes a previous prediction by Harway (1963), who also used the successive equal-appearing intervals task to measure distance. Harway (1963) had his adult observers judge distance on a horizontal grass surface in two different eye-height conditions (kneeling and standing) in the experiment. He found that his observers had a larger underestimation error in the kneeling condition than in the standing condition, although, when the kneeling condition underestimation error was statistically compared with the standing condition underestimation error, the errors were not significantly different.

In our second experiment, we further tested the analysis above by extending the Gilinsky (1951) task from judging distances on a horizontal ground surface to judging distances on ground surfaces with slopes (geographical slants). The latter condition (slope surfaces) has not been explored, and it is unknown whether the Gilinsky equation will hold for it. Figure 2a depicts a ground surface with a physical geographical slant, θ. If the global representation of the ground surface has a slant error (η), we can derive the following trigonometric relationship (Figure 2b):

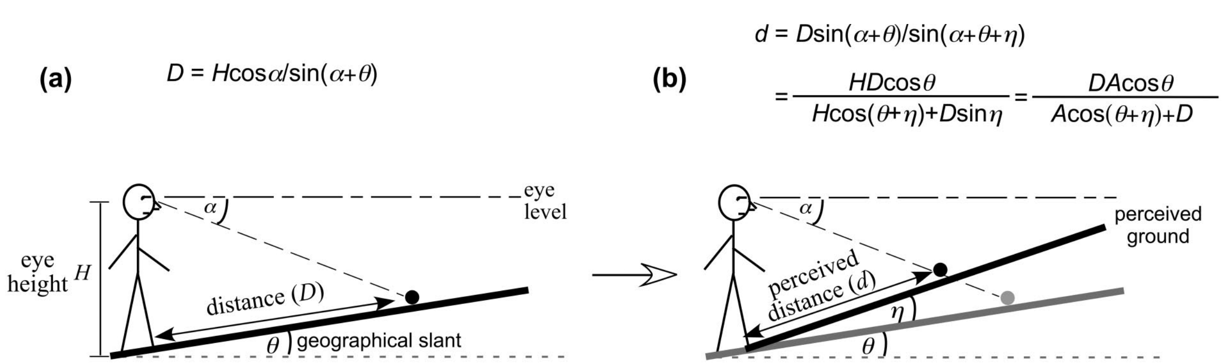

Figure 2. a: An observer judges the distance of a target on a ground surface with a slope (θ). b: The representation of the slant ground surface has a slant error (η), and, accordingly, the perceived target distance is trigonometrically determined by the relationship $d = [DA\cos(\theta)]/[A\cos(\theta + \eta) + D]$.

$$d = \frac{D \sin(\alpha + \theta)}{\sin(\alpha + \theta + \eta)}. \quad (6)$$

Equation 6 can also be expressed as

$$d = \frac{HD \cos \theta}{H \cos(\theta + \eta) + D \sin \eta}. \quad (7)$$

And, if we define $H\cos\theta/\sin\eta = A$, Equation 7 can be rewritten as

$$d = \frac{DA}{A[\cos(\theta + \eta)/\cos \theta] + D}. \quad (8)$$

Noticeably, if the slant error η is much smaller than the physical geographical slant θ, the ratio, $\cos(\theta + \eta)/\cos\theta$, will be close to unity, and Equation 8 takes the same form as Gilinsky's equation (Equation 1). Thus, with Experiment 2, we not only evaluate our analysis on the basis of the ground-surface mechanisms but also generalize the Gilinsky equation to ground surfaces with slopes.

It should be pointed out that Equations 6, 7, and 8 above were derived with the provision that the observer stood at the bottom of the slope (Figure 2) and viewed the targets on the slope along the uphill direction. If the observer stood at the top of the slope and looked in the downhill direction, the corresponding equations would be the same, except the physical geographical slant (θ) would be negative.

Experiment 1: Judging Distance From Different Eye Heights

Method

Observers. Seven observers with informed consent participated in the study. They were naive about our experimental predictions. The observers' eye heights were measured in three conditions: (a) the *stand-on-ground condition* (baseline), where they stood on a horizontal grass surface, (b) the *sit-on-chair condition*, where they sat on a 0.50 m high chair, and (c) the *stand-on-ledge condition*, where they stood on a 0.97 m high ledge. Altogether, their average eye heights in the three conditions were 166.9 cm ($\pm$2.4 cm) for the stand-on-ground condition, 120.6 cm ($\pm$1.4 cm) for the sit-on-chair condition, and 263.9 cm ($\pm$2.4 cm) for the stand-on-ledge condition.

Stimuli and test procedures. All of the three conditions in the experiment were conducted with the targets on the horizontal grass surface. The task of successive equal-appearing intervals similar to Gilinsky's (1951) was used to measure the observers' judgments of distance. Prior to testing, the observers were given a practice session to familiarize them with the task.

At the start of the practice session, a measuring tape was placed on the ground surface directly in front of the observer in the midline with its zero edge touching the front edge of the observer's shoes. The observer was instructed to look from the front edge of his or her shoes to the 2-ft (0.61-m) mark of the measuring tape and to commit this length to memory. Thereafter, the farthest horizontal edge (from the observer's viewpoint) of a horizontal rectangular piece of brown wood (0.5 cm $\times$ 8.8 cm $\times$ 20 cm) was placed at the 2-ft (0.61-m) mark of the measuring tape, and the measuring tape was removed. To start the successive equal-appearing intervals distance judgment measurement, the experimenter placed a second rectangular piece of wood (the same size as the first piece) on the ground about 1.5–3 ft (0.46–0.91 m) away from the first rectangular piece. The observer was then instructed to judge if the distance between the two rectangles (farthest horizontal edge to farthest horizontal edge) was equal to, longer than, or shorter than 2 ft (0.61 m). If the interval was judged to be either longer or shorter, the experimenter would readjust the distance of the second rectangle in the appropriate direction. This procedure of having the observer judge and the experimenter bracket the distance was repeated until the observer felt that the distance between the two rectangles was 2 ft (0.61 m), hence concluding the first successive equal-appearing intervals measurement. A second successive equal-appearing intervals measurement followed, with the experimenter moving the first rectangle (nearest to the observer) to a new location farther than the second rectangle (whose position remained unchanged at where the observer set it during the first measurement). As in the first measurement, the observer now judged whether the interval between the two rectangles was equal to, longer than, or shorter than the memorized 2 ft (0.61 m). With the same judging and bracketing procedure as in the first measurement, the experimenter obtained the physical interval between the two rectangles that gave the observer the subjective percept of 2 ft (0.61 m). Gradually, from the near to the far distance, the experimenter obtained 13–15 measurements of physical intervals that were perceived by the observer as being equal to the perceived length of 2 ft (0.61 m). The actual test sessions began after the practice session and when the observer was comfortable with the task.

During the actual testing, the observer was asked to either close his or her eyes or look away from the rectangular target settings in between measurements, to allow the experimenter to adjust and/or measure the physical distance or interval set. The observer performed the experiments with his or her habitual vision (best corrected binocular vision). The observer was also instructed to avoid making any unnecessary eye, head, or body movements while performing the distance judgments. Each of the three eye-height conditions tested was repeated twice, and the average was taken for data analysis. The order of testing the three eye-height conditions was counterbalanced.

Data analysis. We used the same method as Gilinsky (1951) did to analyze the data in the current experiment (Figure 3) and in the next experiment (Figure 4). We began by deriving the individual observer's physical (egocentric) distances to obtain the relationship between judged distance and physical distance. This was done by accumulating each physical interval that produced an equal perceptual interval (2 ft, or 0.61 m) from near to far. For example, for the first data point, the physical distance was the first physical interval while the judged distance was 2 ft (0.61 m). For the second data point, the physical distance was the summation of the first and second physical intervals while the judged distance was 4 ft (1.22 m). A similar procedure was used to obtain the third, fourth, and other higher order data points. Having done this for each observer, we then took the average of all observers' physical distances and plotted the judged distances as a function of the average physical distances in the graphs presented in Figures 3 and 4 (note that the judged distance, 2 ft, or 0.61 m, was the same for all observers).

It should be pointed out that we have adopted the same method of data analysis and convention as was used by Gilinsky (1951) to

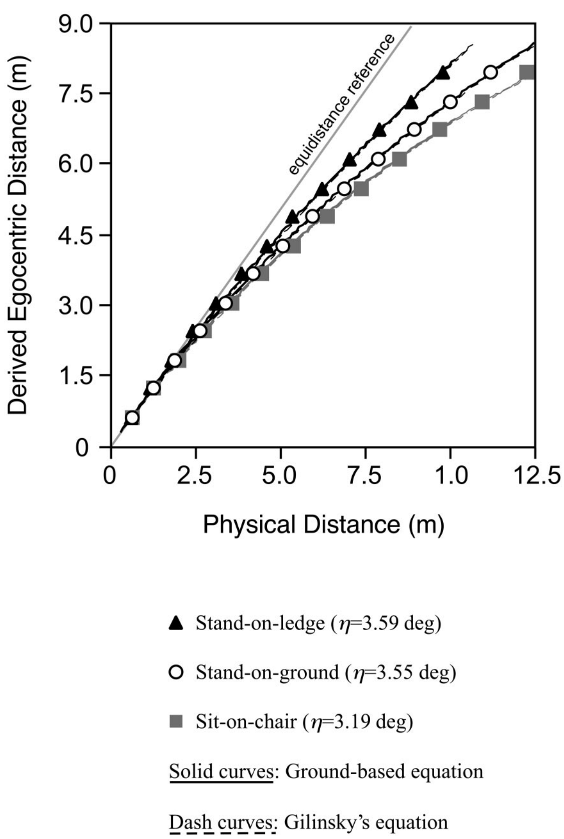

Figure 3. The derived egocentric distances for the three eye-height conditions are plotted as a function of the physical distances. The gray straight line is a reference for an equidistance response. Clearly, distance compression is large when the eye height is small. Each set of symbols is fitted with curves based on our trigonometric analysis (solid-line curve, Equation 4 in the text) and the Gilinsky (1951) equation (dashed-line curve, Equation 1 in the text), respectively. The two types of curves closely overlap in each condition.

be consistent with her study and facilitate our comparison with her data. But we are cognizant of the fact that *distance* as defined by Gilinsky does not carry the same connotation as the phrase *egocentric distance* that is generally used in the current space perception literature. One reason for this is that in the Gilinsky task, the distance is indirectly derived from the observer's response to a set criterion: a remembered distance interval. However, unlike Gilinsky, most current researchers in space perception usually use a more direct task—for example, blind walking—to measure the perceived egocentric distance (e.g., Loomis et al., 1992, 1996; Thomson, 1983). Collectively, these researchers have found that with the more direct task, egocentric distance is generally accurate up to 20–25m. We defer further discussion of the difference between the Gilinsky task and the more direct measures of perceived distance to the General Discussion section. For now, to convey this distinction, we have labeled the *y*-axes in Figures 3 and 4 *derived egocentric distance* instead of *distance*.

Results and Discussion

The graphs for the three eye-height conditions in Figure 3 are plotted using the same data plotting method as Gilinsky (1951) used. They relate the average derived egocentric distance as a function of the physical distance. Two key observations can be made. First, all the data points, except for those at the nearer viewing distances, are clearly below the equidistance diagonal line reference, indicating that the perceived distances were underestimated. Moreover, the magnitude of distance underestimation increased with viewing distance. This observation is in general agreement with Gilinsky's findings. Second, the magnitudes of distance underestimation (perceptual compression of distance) differ among the three eye-height conditions, with the smallest compression of distance occurring when the observer's eye height was largest (in the stand-on-ledge condition). A two-way analysis of variance (ANOVA) with repeated measures reveals a significant difference (intervals) between the sit-on-chair and stand-on-ground conditions; for the main effect of distance, $F(11, 66) = 13.25$, $p < .001$; for the main effect of eye height, $F(1, 6) = 28.86$, $p < .005$; for their interaction, $F(11, 66) = 4.41$, $p < .001$. A second two-way ANOVA with repeated measures reveals a significant difference between the stand-on-ledge and stand-on-ground conditions; for the main effect of distance, $F(11, 66) = 16.80$, $p < .001$; for the main effect of eye height, $F(1, 6) = 8.93$, $p < .025$; for their interaction, $F(11, 66) = 2.23$, $p < .025$. This observation extends the significance of Gilinsky's equation (Equation 1) by indicating that the parameter A is influenced by eye height.

We used the least squares method to fit the data in each eye-height condition with a curve based on Equation 4. Clearly, there is a remarkable agreement between the data points and the derived curves (see the solid lines in Figure 3). The data fitting also allowed us to estimate the slant error in representing the ground surface for each eye-height condition: $\eta = 3.19°$ for the sit-on-chair condition, $\eta = 3.55°$ for the stand-on-ground condition, and $\eta = 3.59°$ for the stand-on-ledge condition. We further applied the η obtained to calculate A, which our earlier analysis, proposes is equal to $H/\sin\eta$. Our calculations show that $A = 21.6$ m for the sit-on-chair condition, $A = 27.0$ m for the stand-on-ground condition, and $A = 42.0$ m for the stand-on-ledge condition. Noticeably, because the η in all three eye-height conditions are about similar in magnitude, our calculations underscore that A increases with the eye height. (If the parameter η was the same magnitude for the three eye-height conditions, parameter A would be exactly proportional to the eye height.)

We also used the least squares method to fit the data in Figure 3 with curves based on Gilinsky's (1951) equation (Equation 1). These curves are depicted with dashed lines. Clearly, they fit the data quite well and more or less overlap with the solid-lined curves based on our equation (Equation 4). We also used Gilinsky's equation to calculate parameter A for the different conditions. These are 21.8 m for the sit-on-chair condition, 27.4 m for the stand-on-ground condition, and 42.6 m for the stand-on-ledge condition.

We proposed in our analysis in the introduction that Equation 5 would take the exact same form as Gilinsky's (1951) equation only if the slant error in representing the ground surface is sufficiently small (so that $\cos\eta \approx 1$). This prediction can be met, given that the ηs estimated from all three eye-height conditions are quite small. For example, with the largest slant error obtained from the stand-on-ledge condition (3.59°), the value of $\cos\eta$ is 0.998, which is close to unity.

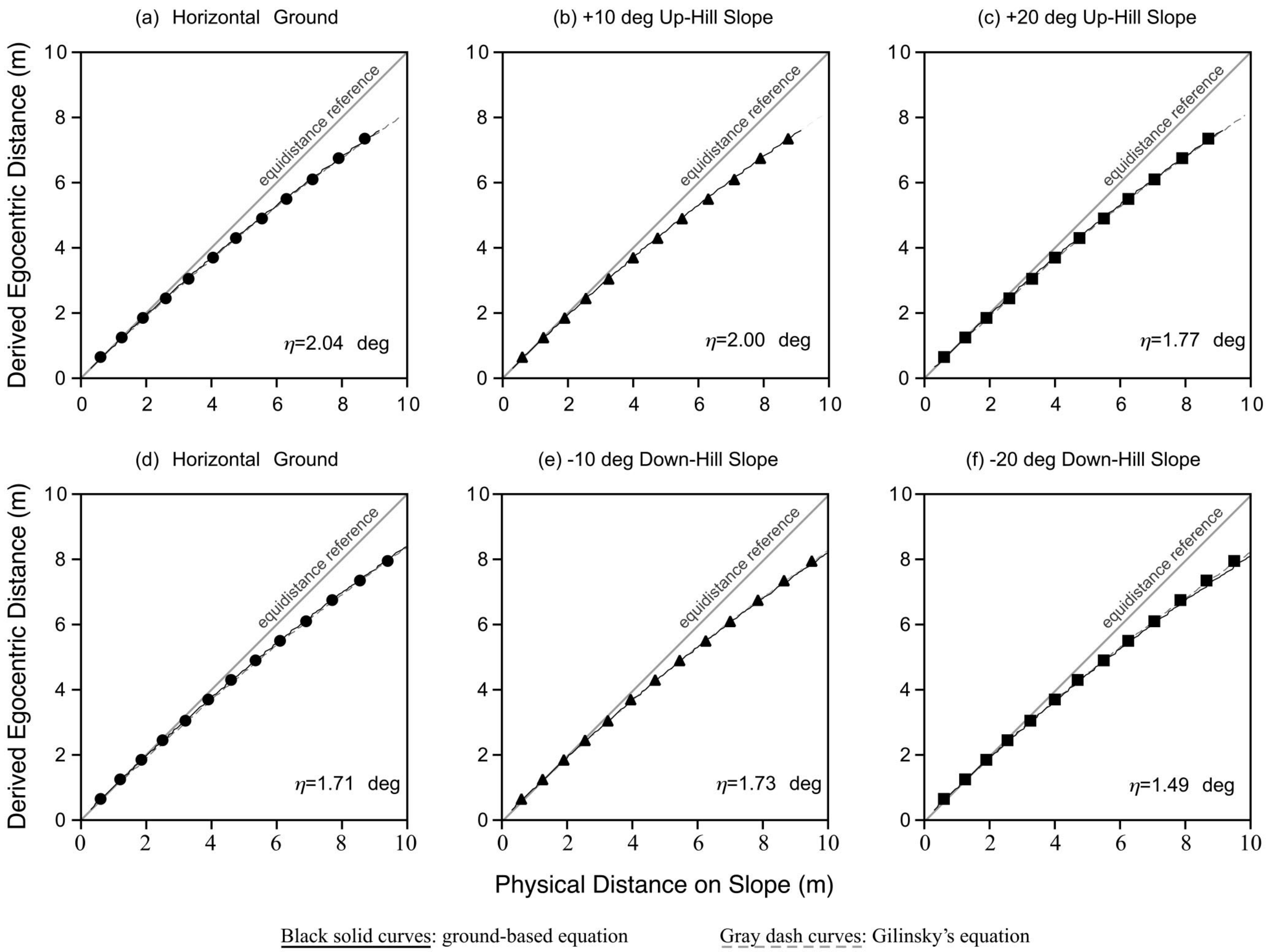

Figure 4. All six graphs plot the derived egocentric distances as a function of the physical distances for the six ground surface conditions tested. Graphs a–c are for the horizontal, +10°, and +20° uphill conditions, and Graphs d–f are for the horizontal, −10°, and −20° downhill conditions, respectively. For each graph, the 45° gray solid line is a reference for an equidistance response. The symbols represent the average data, whereas the black solid-line and gray dashed-line curves fitted to the symbols are based on the trigonometric analysis (Equation 6 in the text) and the Gilinsky (1951) equation (Equation 1 in the text), respectively. Clearly, the solid and dashed curves closely overlap in each condition.

Experiment 2: Judging Distance on Surfaces With Different Slopes or Geographical Slants

Method

Observers. Two groups of new observers who were naive to the purpose of the study participated in the experiment. The first group ($n = 9$) had an average eye height of 156.4 cm (±2.5 cm), and the second group ($n = 6$) had an average eye height of 155.3 cm (±3.8 cm). Both groups were tested on the same horizontal and sloping grass surfaces. The difference in treatment between the two groups was in the viewing conditions on the slopes. Specifically, the first group stood at the bottom of the slopes (uphill conditions) whereas the second group stood at the top of the slopes (downhill conditions) when performing the task. The horizontal grass surface, on which both groups were tested, essentially served as the baseline measure. All observers provided their informed consent before the experiment. They were tested with their habitual vision (best corrected binocular vision).

Stimuli and test procedures. The experiment was conducted at three locations with different geographical slants: 0°, ±10°, and ±20° grass surfaces. The lengths and widths of the surfaces were roughly twice those of the areas used for conducting the measurements. The three types of surfaces were parts of a larger field on the campus grounds. The best parts of the grounds, that is, the areas with plane surfaces rather than curved surfaces, were selected for testing. To choose the appropriate areas, we measured with a protractor the geographical slants of six points along each surface of interest. These points were 2.50, 3.75, 5.00, 6.25, and 7.50 m from the starting point (assuming an uphill condition). The geographical slant of the 0° surface condition was 0° for all six points. The geographical slants of the 10° surface condition were 10° for all points except the starting point, which was 9°. The geographical slants of the 20° surface condition were 20° for all except two points: The slant at the 5.00-m point was 19° and the slant at the starting point was 15°.

The same task of successive equal-appearing intervals that was used in Experiment 1 was used in Experiment 2. Also similar to Experiment 1, the targets were two flat wooden rectangles of the same size (0.5 cm × 8.8 cm × 20 cm), but they were painted red. The observers were given a practice session before we conducted the experiment.

The three conditions tested in the first group of observers were the horizontal condition, the +10° uphill condition, and the +20° uphill condition. As mentioned above, the observers stood at the bottom of the slopes in the uphill conditions. The targets used to measure the perceived 2-ft (0.61-m) interval were successively located uphill along the slopes relative to the observers.

Similarly, the three conditions tested in the second group of observers were the horizontal condition, the −10° downhill condition, and the −20° downhill condition. Here, the targets were successively located downhill along the slopes relative to the observers.

Results and Discussion

The three graphs in Figure 4a–4c plot the average data of the horizontal, the +10° uphill condition, and the +20° uphill condition, respectively. The *x*-axes represent the physical distances on the horizontal and slant surfaces and the *y*-axes represent the derived egocentric distances on the horizontal and slant surfaces. The data points in all three conditions show a similar trend. All the data points, except for those representing the nearer physical distances, are below the equidistance diagonal line references. This indicates an underestimation of perceived distance. The underestimation also increased at larger physical distances.

For all three conditions, we used the least squares method to fit the data points with curves based on Equation 6. As can be seen in Figure 4a–4c, the black solid-lined curves fit the data quite well when we assume that the slant errors in representing the ground surface for the three conditions are 2.04° for the horizontal condition, 2.00° for the +10° uphill condition, and 1.77° for the +20° uphill condition. These estimated slant errors are very close to one another despite the different geographical slants of the ground surfaces. Using the estimated slant errors, we further calculated the parameter *A* from the relationship $A = H\cos\theta/\sin\eta$. We found that A = 44.04 m for the horizontal condition, A = 42.24 m for the +10° uphill condition, and A = 44.04 m for the +20° uphill condition. We also used the least squares method to fit the data with the Gilinsky (1951) equation (Equation 1) to verify if her equation applies to judged distances on the slopes. The curves based on Gilinsky's equation are plotted with gray dashed lines in Figure 4a–4c. Clearly, they not only fit the data well but are also very close to the black solid-lined curves based on Equation 6. Parameter *A*, calculated on the basis of the Gilinsky equation, is 44.23 m for the horizontal condition, 44.75 m for the +10° uphill condition, and 45.28 m for the +20° uphill condition. Finally, according to our earlier analysis, Equation 8 will take the same form as Gilinsky's equation if the ratio $\cos(\theta + \eta)/\cos(\theta)$ is close to unity (i.e., η is much smaller than θ). Our calculation of the ratio indicates that this requirement can be met; the ratio for the horizontal condition is 0.999, for the +10° uphill condition is 0.993, and for the +20° uphill condition is 0.988.

The same data analyses as above were applied to the average data from the horizontal, −10° downhill, and −20° downhill conditions, whose graphs are plotted in Figure 4d–4f. Overall, the data appear similar to those in the uphill conditions. In particular, the observers also underestimated distances in the −10° and −20° downhill conditions. This suggests that the slant errors in representing the ground surface are positive, that is, the slopes of the surfaces were perceived as being less slanted when viewed along the downhill direction. The solid-lined curves based on Equation 6 (using the least squares method) fit the data points in all three conditions, when the slant errors are assumed to be 1.71° for the horizontal condition, 1.73° for the −10° downhill condition, and 1.49° for the −20 downhill condition. Noticeably, these values are quite close to one another. We calculated parameter *A* for each condition and found that A = 52.13 m for the horizontal condition, A = 50.81 m for the −10° downhill condition, and A = 49.58 m for the −20° downhill condition. We also used the least squares method to fit the data with Gilinsky's (1951) equation (Equation 1). These curves (dash-lined curves in Figure 4d–4f) provide relatively good fits to the data and are very similar to the solid-lined curves based on Equation 6. Parameter *A*, calculated on the basis of the Gilinsky equation, is 52.33 m for the horizontal condition, 47.82 m for the −10° downhill condition, and 46.53 m for the −20° downhill condition.

Overall, the current experiment demonstrates that our theoretical analysis based on the ground-surface mechanisms of space perception in the intermediate distance range can be applied to the derived egocentric distances on horizontal and slant surfaces (±10°, ±20°). Furthermore, our empirical data show that the Gilinsky (1951) equation can be generalized to slant surfaces, in which parameter *A* is determined by the eye height, the geographical slant, and the slant error in representing the ground surface ($A = H\cos\theta/\sin\eta$).

General Discussion

We have applied a geometrical analysis along with our knowledge of the mechanisms of space perception to derive the relationship between perceived and physical distances (Equations 2–8) with data obtained using Gilinsky's (1951) successive equal-appearing intervals task. Our experiments demonstrated that the derived egocentric distance data at various eye heights and geographical slants of the ground surface tested could be fitted from a geometrical analysis. We also found that our data could be fitted with curves based on the classical Gilinsky equation (Equation 1). The latter finding is also, in fact, predicted from our geometrical analysis, which shows that the trigonometrically based distance relationships assume the same form as Gilinsky's equation when the slant error in representing the ground surface is small. More generally, our study reveals that parameter *A* in Gilinsky's equation is dictated by the eye height and slant error in representing the ground surface, which reaffirms the important role of the ground surface in intermediate-distance space perception (Gibson, 1950, 1979; Sedgwick, 1986).

The Meaning of Parameter A

Recognizing that parameter A in the Gilinsky (1951) equation varies with eye height and slant error helps clarify some puzzling implications of the Gilinsky equation in space perception. For example, parameter A has been treated as an index related to the extent of distance compression. Parameter A in Gilinsky's study was around 28.5 m when an observer stood on a horizontal ground surface. According to Gilinsky's equation, the observer's perception of distance will almost reach an asymptote at a moderately far distance. For instance, at 300 m, a 1-m rod will be perceived as being less than 0.75 cm in length. A strict adherence to Gilinsky's formulation would predict that the 1-m rod would be perceived as being less than 0.75 cm even if the observer was to view the rod from atop a building or from an airplane. But this prediction clearly contradicts the common experience in which the distance interval of objects at a far distance is better perceived from a higher altitude (Loomis & Philbeck, 1999). Nevertheless, this contradiction can be bridged with our finding in Experiment 1, where we revealed that parameter A is not a constant but increases with the eye height. An increase in parameter A reduces the distance compression, thus permitting a better percept of the distance interval when viewed from a higher altitude.

According to our analysis based on the space perception mechanisms, along with the horizontal ground surface being represented as a slant surface, the perceived distance on the horizontal ground is compressed (Figure 5). The intersection of the slant surface representation and the eye level marks the location where the infinite far point on the ground is perceived. This means that the entire ground surface is represented as a slant surface with the maximum distance on the slope being $H/\sin(\eta)$. Recall that we pointed out earlier that when the slant error of the perceived ground surface is very small, parameter A of Gilinsky's equation can be approximated by $H/\sin(\eta)$. In this regard, parameter A can be considered the maximum distance on the represented ground surface (Figure 5). This suggestion corresponds with the prevailing view that parameter A is the asymptotic limit of the perceived distance on the ground (Gilinsky, 1951).

Gilinsky (1951) pointed out that the value of parameter A for an individual depends on the available depth cues, for example, during binocular versus monocular viewing. (A larger parameter A is found when more depth cues are available, which increase the accuracy of distance judgment.) This insightful suggestion finds a parallel in our geometrical analysis based on space perception mechanisms. Because our analysis shows that parameter A can also be defined as $H/\sin\eta$, it means that if the eye height remains unchanged, distance judgment is further underestimated when the slant error in representing the ground surface is large. With regard to η, our previous research using other types of distance judgment tasks has suggested that the slant error increases when the depth cues on the ground surface are either unavailable or ineffective (Ooi et al., 2001, 2006; B. Wu et al., 2004; J. Wu et al., 2004). For instance, as mentioned earlier, J. Wu et al. (2004, 2006) measured egocentric distance judgments in a no-depth cue condition (dark environment) and a partial-depth cue condition (several phosphorescent elements formed a textured-ground surface in an otherwise dark environment). It was found that the approximated slant error was larger in the no-depth cue condition than in the partial-depth cue condition.

The Slant Error of the Ground-Surface Representation

As discussed above and in the introduction, when the viewing condition is not optimal, the SSIP represents the ground surface with a slant error and the visual system underestimates the distance (the slant surface hypothesis; Figure 6a). Arguably, it is also possible that the underestimation of distance can occur on a ground surface that is horizontally compressed (the horizontal compression hypothesis; see Figure 6b). Nevertheless, there are reasons to believe that the visual system is unlikely to adopt the horizontal compression scheme (Ooi et al., 2006). One main consideration is that if the ground surface were horizontally compressed, the subjective angular declination of the objects on the ground would have to be increased (Figure 6b). But the latter condition is not supported by various empirical observations, which show that the human observer makes accurate direction judgments under most viewing conditions even as he or she underestimates the distance (e.g., Loomis et al., 1992; Ooi et al., 2001, 2006; also see Sedgwick, 1986). For example, we showed that although the judged location of a dimly lit target in the dark environment where the ground surface is not visible is inaccurate, the judged angular declination of the target remains largely veridical (Ooi et al., 2001). Other empirical evidence for the slant surface hypothesis exists, as discussed earlier. Finally, in several of our previous studies (e.g., He et al., 2004; Ooi et al., 2006; B. Wu et al., 2004, in press-a; J. Wu et al., 2004, 2006), we have found that the slant surface assumption analysis can be used to fit our empirical findings.

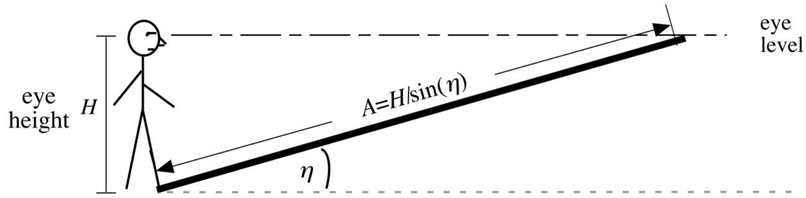

Figure 5. An illustration of the meaning of parameter A in the Gilinsky (1951) equation. A horizontal ground surface is represented as a slant surface with a geographical slant of η. In the perceptual space, the intersection of the slant surface and the eye level specifies the location where the infinite far point of the ground surface is represented. As such, it sets the upper limit of the distance on the ground surface that can be perceived, which is $H/\sin\eta$. It is interesting that if the slant error η is very small, this upper limit of perceived distance is very close to the parameter A specified by Gilinsky's equation (Equation 1 in the text).

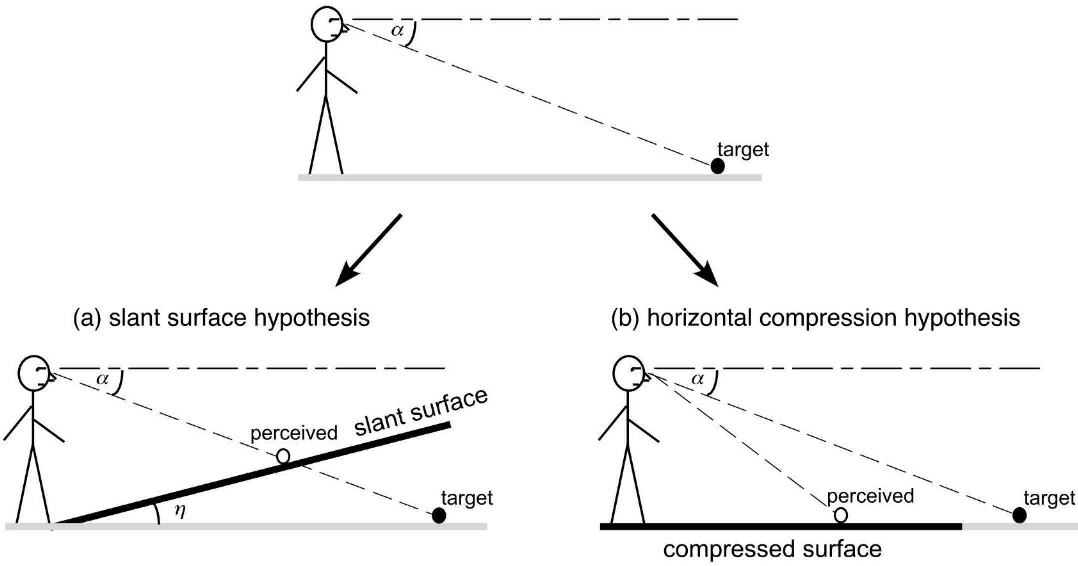

Figure 6. Illustration of two possible ground-surface representations of a horizontal ground surface in perceptual distance underestimation. a: The slant surface hypothesis states that the horizontal ground is represented as a slant surface. The perceived target distance on the slanted ground surface representation is shorter than the physical target distance on the horizontal ground surface; that is, the perceived target distance is underestimated. b: The horizontal compression hypothesis states that the horizontal ground is represented as a horizontal surface that is horizontally compressed toward the observer. The perceived target distance on the horizontally represented ground is reduced. Although both hypotheses predict distance underestimation, the horizontal compression hypothesis does not accurately maintain the target's direction (angular declination).

The slant surface hypothesis also provides an insight into the observation that the magnitude of distance underestimation becomes larger as the physical distance of the target increases. Although this observation is often attributed to the fact that the depth cues become less effective at the far distance, the causal factor(s) is (are) less clear. At the same time, it is also known that the underestimation of distance is closely related to the optical slant of the target on the ground, that is, the angle formed between the line of sight to the target and the ground surface (Loomis & Philbeck, 1999; Loomis, Philbeck, & Zahorik, 2002; Ooi et al., 2006; Sedgwick, 1986). Because the optical slant decreases as the target distance on the ground increases, one has to dissociate between these two factors in evaluating their effects on space perception. To do so, Loomis and Philbeck (1999) asked their observers to stand at different heights, which changed the target's optical slant for the given distance, to judge the aspect ratio of an L-shaped target on the ground (an exocentric depth task) in the full cue environment. They found that the judged aspect ratios changed as the height increased (resulting in less foreshortening) for the same viewing distance. By using a similar protocol but conducting it in the dark and by changing the height of the L-shaped target above the horizontal ground, we also found that the judged aspect ratio is a function of the optical slant. Further, we showed that our results could be explained by the proposal that the L-shaped target was perceived as if it were laying on a slant ground-surface representation (Ooi et al., 2006). In other words, the perceived relative depth of an interval is a function of both the optical slant and the representation of the ground surface (with a slant error).

We further suggest that this view can be generalized to egocentric distance perception. Reconsider Equation 6 and assume that the horizontal ground surface is a special case where θ equals zero. Thus, Equation 6 can be rewritten as

$$d/D = \frac{\sin(\alpha + \theta)}{\sin(\alpha + \theta + \eta)}. \tag{9}$$

Because $\alpha + \theta$ is the optical slant, the equation reveals that the ratio of the perceived distance (d) to the physical distance (D) is a function of both the optical slant and the slant error in ground-surface representation. Accordingly, if the slant error in ground-surface representation remains constant over the entire expanse of the ground surface (i.e., the representation is a perfectly slant plane), the ratio that reflects distance underestimation will vary solely as a function of the optical slant from the near to far distance. However, this provision rests on the assumption that the depth information at the distant ground surface is sufficiently effective for the visual system to represent the ground surface as a plane surface with a constant slant error.

So how does the above analysis of Equation 9 explain the observation that the magnitude of distance underestimation increases with viewing distance? According to Equation 9, the ratio d/D decreases as the angular declination decreases. When one stands on the horizontal ground, the angular declination decreases with increasing viewing distance. As such, the ratio d/D decreases as the viewing distance increases. Of course, this explanation is based on the assumption or approximation that the perceived ground surface is a slanted plane surface. However, we believe that the slant error in ground-surface representation actually increases with distance, therefore causing the represented surface to be curved rather than planar with a constant slant error. Consistent with this, our previous empirical investigations revealed that the intrinsic bias takes the form of an implicit surface that is more curved as the distance increases (Ooi et al., 2001, 2006). Thus, relating back to Equation 9, in the case where the visual system cannot efficiently discriminate the texture patterns on the distant ground surface, the SSIP will increase its reliance on the intrinsic bias as it integrates the more distant surface patches, causing the distant ground surface to be represented with an increasing slant error. As such, targets located at the far distant ground surface will be increasingly underestimated (more so than predicted by Equation 9) as the slant error increases with distance.

From the foregoing paragraphs, it is clear that to be stringent, one should model the ground surface representation using a curved surface template. But in the approach used in this and our previous studies, we have approximated the ground-surface representation as a plane surface with a constant slant error. The main reason for doing so is because our constant slant error approximation model provides a sufficiently good fit to our data over the distance range tested. Our ability to assume a constant slant error also reveals that the slant error in representing the ground surface in the intermediate distance range must not be very large, which may explain why one does not usually notice that the horizontal ground surface over this range is curved.

The Fidelity of the Proposed Trigonometric Relationship

Throughout this article, our analysis has focused mainly on how judged distance is related to the slant error in ground-surface representation, under the premise that the angular declination is accurately represented. Can the equations derived from our analysis still be applied if this assumption is violated? For instance, what if the perceived eye level, which serves as the reference for angular declination, is shifted? Figure 7a depicts a scenario where the perceived eye level is deviated above the true eye level (β), leading to an increase in the perceived angular declination. Accordingly, in the perceptual space shown in Figure 7b, the perceived angular declination of an object with physical angular declination α will be $\alpha + \beta$. Taking this together with the slant error in ground-surface representation being δ, we can obtain the perceived distance (d) according to the relationship below:

$$d = \frac{H\cos(\alpha + \beta)}{\sin(\alpha + \beta + \delta)}.$$

If we assume $h = b + d$ and β is small, we can rewrite the equation above as

$$d = \frac{H\cos(\alpha + \beta)}{\sin(\alpha + \eta)} \approx \frac{H\cos(\alpha)}{\sin(\alpha + \eta)}. \tag{10}$$

Noticeably, Equation 10 above takes the same form as Equation 3 but with a slightly different definition for η. In Equation 3, where an accurate perceived angular declination is assumed, η is the slant error in ground-surface representation, whereas in Equation 10, η is equal to the sum of the error in the perceived angular declination and the slant error in ground-surface representation, $\beta + \delta$. Therefore, one can still apply the trigonometric relationship to a scenario in which a small error in perceived angular declination exists, only now the meaning of η is modified.

The Gilinsky (1951) Task and the Difference Between Egocentric and Exocentric Distance Tasks

By introducing and using the blind-walking task, Thomson (1983) showed that a human observer can accurately judge the egocentric distance of an object up to 21 m away. A number of subsequent studies have confirmed Thomson's finding (e.g., Elliott, 1987; Fukusima, Loomis, & Da Silva, 1997; Loomis et al., 1992, 1996; Philbeck, Loomis, & Beall, 1997; Rieser, Ashmead, Talor, & Youngquist, 1990; Sinai et al., 1998; Steenhuis & Goodale, 1988). Clearly, the larger extent of the viewing distance in which perceived distance remains accurate far exceeds what one would predict on the basis of Gilinsky's (1951) study. Such a difference in the experimental outcomes between Thomson's and Gilinsky's studies also highlights the fact that the choice of experimental task can significantly determine the data obtained (Loomis et al., 1996). As for other types of egocentric distance tasks,

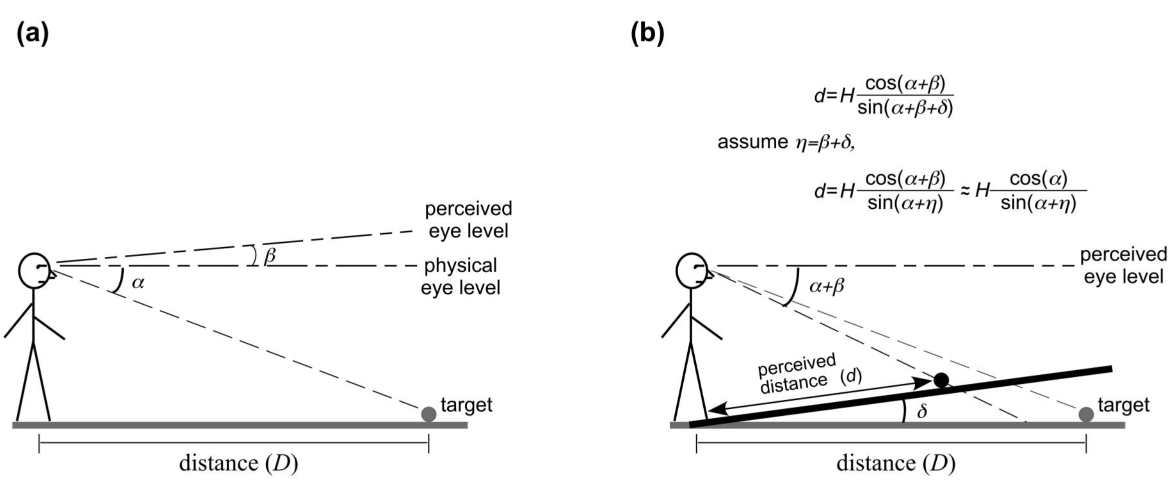

Figure 7. a: A scenario where the perceived eye level is deviated above the true eye level (β), leading to an increase in the perceived angular declination of the target. b: In the perceptual space, the perceived angular declination of the target with a physical angular declination of α is $\alpha + \beta$.

Loomis and Philbeck (in press) recently reviewed several studies that used the verbal report task (which is less objective than the blind-walking task). They pointed out that the judged egocentric distances from the verbal report task can be fitted well by a linear function with an average slope of ~0.8. For the blind-throwing task in the full cue environment, the judged egocentric distances are underestimated (Eby & Loomis, 1987; He et al., 2004; B. Wu, He, & Ooi, in press-b), and can also be fitted well by a hyperbolic function (the Gilinsky equation), although the magnitude of underestimation is smaller than that obtained with an exocentric distance task (Eby & Loomis, 1987).

Since the study by Thomson (1983), others have also established that the human observer underestimates relative depth (exocentric distance) but makes accurate egocentric distance judgments in the intermediate distance range under optimal cue conditions (Loomis et al., 1992, 1996, 2002; Loomis & Philbeck, 1999; Ooi et al., 2006; Philbeck & Loomis, 1997; B. Wu et al., 2004; J. Wu et al., 2005). For example, Loomis and his colleagues conducted a series of systematic experiments to compare exocentric and egocentric distance performances in similar visual environments (Loomis et al., 1992, 1996, 2002; Loomis & Philbeck, 1999; Philbeck & Loomis, 1997). They measured the observer's perceived egocentric distance by using the blind-walking task and found that the observer could walk accurately to a target located in the intermediate distance range. In contrast, the observer's perceived exocentric distance was significantly foreshortened (Loomis et al., 1992, 2002; Loomis & Philbeck, 1999). To address the difference between the two types of distance judgment tasks, Loomis and his colleagues suggested that in the intermediate distance range, egocentric distance is accurately perceived whereas relative distance (or shape) is perceived with a systematic error, and that such a functional dissociation likely occurs at the level of perceptual representation.

One possible factor causing the difference in results between the exocentric and egocentric tasks could be related to how the visual system samples or selects the depth information on the ground surface (He et al., 2004; Ooi et al., 2006; B. Wu et al., 2004). Because the nature of the tasks is different, information selected by the visual system to perform the two tasks could be different, which in turn affects the representation of the ground surface and hence the accuracy of the perceptual space (we refer to this as the *selection hypothesis*). Specifically, for one to perform the blind-walking task accurately, the visual system has to sample the entire ground surface from one's feet up to the target and beyond. But to judge the exocentric distance of a target in the intermediate distance range, the visual system most likely samples predominantly from the ground surface around the target, which does not include the near ground surface. Without the reliable depth information from the near ground surface, the SSIP cannot form an accurate ground-surface representation. Accordingly, the visual system cannot obtain an accurate exocentric distance. (One implication of the selection hypothesis is that the difference between judged egocentric and exocentric distances could reflect, in part, the shape of the perceptual space while an observer performs each task. This implication differs from the view that the difference is due to two dissimilar distance-assessing processes that operate in the same perceptual space.) Supporting this explanation, a separate study from our laboratory measured the observer's perception of the length of a rod (relative depth) in two conditions (J. Wu et al., 2005). In the test condition, the observer scanned both the near ground surface and the ground surface surrounding the rod. In the control condition, he or she looked only at the ground around the rod beyond the near ground surface. We found that the perceived length of the rod (relative depth) was more accurate in the test condition, in support of the sampling explanation.

In our current study, we used the successive equal-appearing intervals task to measure observers' judgments of distance (Gilinsky, 1951). During the task, the observer matched the length of an interval on the ground with a remembered length (a 2-ft [0.61-m] interval). Although this distance task measures perceived exocentric distance, we, as Gilinsky (1951) did, derived egocentric distance from the data obtained by integrating the judged distance intervals (from the exocentric distance task) from near to far. Admittedly, this method of deriving perceived egocentric distance from an exocentric distance task has been questioned in the space perception literature (e.g., Loomis & Philbeck, 1999). This is because the derived egocentric distance, which is based on an exocentric distance judgment task, may not be equated to that obtained directly from an egocentric distance task because two different perceptual operations are likely to be responsible for the two tasks (Loomis et al., 1992, 2002).

Nevertheless, we emphasize that although the egocentric distance and exocentric distance tasks lead to different accuracy of judged distance, they share an important common feature: the use of the ground-surface representation as a reference frame. This is why both the perceived egocentric and the exocentric distance data can be modeled by the trigonometric relationships that are motivated by the space perception mechanisms. For example, the magnitude of distance underestimation in both tasks can be modeled by a ground surface with an upward slant error (Ooi et al., 2001, 2006; B. Wu et al., 2004; J. Wu et al., 2004).

To conclude on a historical note, more than 50 years ago, two researchers independently made their contributions to the field of space perception. Gibson (1950) introduced the ground theory of space perception that emphasizes the importance of the ground surface for distance judgment. Meanwhile, Gilinsky (1951) introduced a quantitative function to relate the physical and perceived distances. It is gratifying that the insight derived from the ground theory of space perception successfully provides a theoretical basis for the Gilinsky equation, which fits the distance judgment data remarkably well.

References

Baird, J. C., & Biersdorf, W. R. (1967). Quantitative functions for size and distance judgments. *Perception & Psychophysics, 2,* 161–166.

Beusman, J. M. H. (1998). Optic flow and the metric of the visual ground plane. *Vision Research, 38,* 1153–1170.

Bian, Z., Braunstein, M. L., & Andersen, G. J. (2005). The ground dominance effect in the perception of 3-D layout. *Perception & Psychophysics, 67,* 815–828.

Creem-Regehr, S. H., Willemsen, P., Gooch, A., & Thompson, W. B. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual indoor environments. *Perception, 34,* 191–204.

Cutting, J. E., & Vishton, P. M. (1995). Perceiving layout and knowing distance: The integration, relative potency, and contextual use of different information about depth. In W. Epstein & S. Rogers (Eds.), *Handbook of perception and cognition: Perception of space and motion* (Vol. 5, pp. 69–117). San Diego, CA: Academic Press.

Da Silva, J. (1985). Scales for perceived egocentric distance in a large open field: Comparison of three psychological methods. *American Journal of Psychology, 98,* 119–144.

Dolezal, H. (1982). *Living in a world transformed: Perceptual and performatory adaptation to visual distortion*. New York: Academic Press.

Eby, D. W., & Loomis, J. M. (1987). A study of visually directed throwing in the presence of multiple distance cues. *Perception & Psychophysics, 41,* 308–312.

Elliott, D. (1987). Continuous visual information may be important after all: A failure to replicate Thomson (1983). *Journal of Experimental Psychology: Human Perception and Performance, 12,* 388–391.

Feria, C. S., Braunstein, M. L., & Andersen, G. J. (2003). Judging distance across texture discontinuities. *Perception, 32,* 1423–1440.

Foley, J. M. (1980). Binocular distance perception. *Psychological Review, 87,* 411–434.

Foley, J. M., Ribeiro, N. P., & Da Silva, J. A. (2004). Visual perception of extent and the geometry of visual space. *Vision Research, 44,* 147–156.

Fukusima, S. S., Loomis, J. M., & Da Silva, J. A. (1997). Visual perception of egocentric distance as assessed by triangulation. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 86–100.

Gibson, J. J. (1950). *The perception of the visual world.* Boston: Houghton Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Hillsdale, NJ: Erlbaum.

Gilinsky, A. S. (1951). Perceived size and distance in visual space. *Psychological Review, 58,* 460–482.

Gogel, W. C. (1977). The metric of visual space. In W. Epstein (Ed.), *Stability and constancy in visual perception: Mechanisms and processes* (pp. 129–181). New York: Wiley.

Hagen, M. A., Jones, R. K., & Reed, E. S. (1978). On a neglected variable in theories of pictorial perception: Truncation of the visual field. *Perception & Psychophysics, 23,* 326–330.

Harway, N. I. (1963). Judgment of distance in children and adults. *Journal of Experimental Psychology, 65,* 385–390.

He, Z. J., & Ooi, T. L. (2000). Perceiving binocular depth with reference to a common surface. *Perception, 29,* 1313–1334.

He, Z. J., Wu, B., Ooi, T. L., Yarbrough, G., & Wu, J. (2004). Judging egocentric distance on the ground: Occlusion and surface integration. *Perception, 33,* 789–806.

Loomis, J. M., Da Silva, J., Fujita, N., & Fukusima, S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 906–921.

Loomis, J. M., Da Silva, J. A., Philbeck, J. W., & Fukusima, S. S. (1996). Visual perception of location and distance. *Current Directions in Psychological Science, 5,* 72–77.

Loomis, J. M., & Philbeck, J. W. (1999). Is the anisotropy of perceived 3-D shape invariant across scale? *Perception & Psychophysics, 61,* 397–402.

Loomis, J. M., & Philbeck, J. W. (in press). Measuring perception with spatial updating and action. In R. L. Klatzky, M. Behrmann, & B. MacWhinney (Eds.), *Embodiment, ego-space, and action.* Mahwah, NJ: Erlbaum.

Loomis, J. M., Philbeck, J. W., & Zahorik, P. (2002). Dissociation of location and shape in visual space. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1202–1212.

Luneburg, R. K. (1947). *Mathematical analysis of binocular vision*. Princeton, NJ: Princeton University Press.

MacDougall, R. (1903). The subjective horizon. *Psychological Monographs, 4*(1, Suppl.), 145–166.

Madison, C., Thompson, W., Kersten, D., Shirley, P., & Smits, B. (2001). Use of inter-reflection and shadow for surface contact. *Perception & Psychophysics, 63,* 187–194.

Matin, L., & Li, W. (1994). Spatial summation among coextensive and parallel line segments across wide separations (50°): Egocentric localization and the great circle model. *Vision Research, 34,* 2577–2598.

Meng, J. C., & Sedgwick, H. A. (2001). Distance perception mediated through nested contact relations among surfaces. *Perception & Psychophysics, 63,* 1–15.

Meng, J. C., & Sedgwick, H. A. (2002). Distance perception across spatial discontinuities. *Perception & Psychophysics, 64,* 1–14.

Ni, R., Braunstein, M. L., & Andersen, G. J. (2004). Perception of scene layout from optical contact, shadows, and motion. *Perception, 33,* 1305–1318.

Ooi, T. L., & He, Z. J. (2006). Localizing suspended objects in the intermediate distance range (>2 meters) by observers with normal and abnormal binocular vision [Abstract]. *Journal of Vision, 6,* 422a. Retrieved January 10, 2007, from http://journalofvision.org/6/6/422/

Ooi, T. L., Wu, B., & He, Z. J. (2001, November 8). Distance determined by the angular declination below the horizon. *Nature, 414,* 197–200.

Ooi, T. L., Wu, B., & He, Z. J. (2006). Perceptual space in the dark affected by the intrinsic bias of the visual system. *Perception, 35,* 605–624.

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 72–85.

Philbeck, J. W., Loomis, J. M., & Beall, A. C. (1997). Visually perceived location is an invariant in the control of action. *Perception & Psychophysics, 59,* 601–612.

Rieser, J. J., Ashmead, D., Talor, C., & Youngquist, G. (1990). Visual perception and the guidance of locomotion without vision to previously seen targets. *Perception, 19,* 675–689.

Sedgwick, H. A. (1986). Space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 21.1–21.57). New York: Wiley.

Sedgwick, H. A. (1989). Combining multiple forms of visual information to specify contact relations in spatial layout. In P. S. Schenker (Ed.), *SPIE Proceedings: Vol. 1198. Sensor fusion II: Human and machine strategies* (pp. 447–458). Bellingham, WA: International Society for Optical Engineering.

Shah, D., & Sedgwick, H. A. (2004). Spatial compression and adaptation with the low vision telescope. *Optometry and Vision Science, 81,* 785–793.

Sinai, M. J., Ooi, T. L., & He, Z. J. (1998, October 1). Terrain influences the accurate judgement of distance. *Nature, 395,* 497–500.

Steenhuis, R. E., & Goodale, M. A. (1988). The effects of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist? *Journal of Motor Behavior, 20,* 399–415.

Stoper, A. E., & Cohen, M. M. (1986). Judgments of eye level in light and darkness. *Perception & Psychophysics, 40,* 311–316.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance, 9,* 427–443.

Toye, R. C. (1986). The effect of viewing position on the perceived layout of space. *Perception & Psychophy*sics, *40,* 85–92.

Wagner, M. (1985). The metric of visual space. *Perception & Psychophysics, 38,* 483–495.

Wu, B., He, Z. J., & Ooi, T. L. (2002). A ground surface based space perception in the virtual environment [Abstract]. *Journal of Vision, 2,* 513a. Retrieved January 12, 2007, from http://journalofvision.org/2/7/513/

Wu, B., He, Z. J., & Ooi, T. L. (in press-a). Inaccurate representation of the ground surface beyond a texture boundary. *Perception.*

Wu, B., He, Z. J., & Ooi, T. L. (in press-b). The linear perspective information in ground surface representation and distance judgment. *Perception & Psychophysics.*

Wu, B., Ooi, T. L., & He, Z. J. (2004, March 4). Perceiving distance accurately by a directional process of integrating ground information. *Nature, 428,* 73–77.

Wu, J., He, Z. J., & Ooi, T. L. (2004). Stimulus duration and binocular disparity factors in representing the ground surface and localizing object in the intermediate distance range [Abstract]. *Journal of Vision, 4,* 21a. Retrieved January 12, 2007, from http://journalofvision.org/4/8/21/

Wu, J., He, Z. J., & Ooi, T. L. (2006). The slant of the visual system's intrinsic bias in space perception and its contribution to ground surface representation [Abstract]. *Journal of Vision, 6,* 730a. Retrieved January 12, 2007, from http://journalofvision.org/6/6/730/

Wu, J., Ooi, T. L., & He, Z. J. (2005). Visually perceived eye level and horizontal midline of the body trunk influenced by optic flow. *Perception, 34,* 1045–1060.

Received October 21, 2005
Revision received November 8, 2006
Accepted November 9, 2006 ■

Call for Papers *Journal of Experimental Psychology: Learning, Memory, and Cognition*
Special Section on Source Memory: Integrating Cognitive Behavioral and Cognitive Neuroscience Approaches

The *Journal of Experimental Psychology: Learning, Memory, and Cognition* invites manuscripts for a special section on source memory, to be compiled by guest editors Marcia K. Johnson and Mieke H. Verfaellie, working together with journal Associate Editor John Dunlosky. The goal of the special section is to showcase high-quality research that brings together behavioral, neuropsychological, and neuroimaging approaches to understanding the cognitive and neural bases of source memory. We are seeking cognitive behavioral studies that integrate cognitive neuroscience findings in justifying hypotheses or interpreting results and cognitive neuroscience studies that emphasize how the evidence informs cognitive theories of source memory. In addition to empirical papers, focused review articles that highlight the significance of cognitive neuroscience approaches to cognitive theory of source memory are also appropriate.

The submission deadline is June 1, 2007. The main text of each manuscript, exclusive of figures, tables, references, or appendixes, should not exceed 35 double-spaced pages (approximately 7,500 words). Initial inquiries regarding the special section may be sent to John Dunlosky (jdunlosk@kent.edu), Marcia K. Johnson (marcia.johnson@yale.edu), or Mieke H. Verfaellie (verf@bu.edu). Papers should be submitted through the regular submission portal for *JEP: Learning, Memory, and Cognition* (http://www.apa.org/journals/xlm/submission.html) with a cover letter indicating that the paper is to be considered for the special section. For instructions to authors and other detailed submission information, see the journal Web site at http://www.apa.org/journals/xlm.