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Perceptual space in the dark affected by the intrinsic bias of the visual system

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Abstract. Correct judgment of egocentric/absolute distance in the intermediate distance range requires both the angular declination below the horizon and ground-surface information being represented accurately. This requirement can be met in the light environment but not in the dark, where the ground surface is invisible and hence cannot be represented accurately. We previously showed that a target in the dark is judged at the intersection of the projection line from the eye to the target that defines the angular declination below the horizon and an implicit surface. The implicit surface can be approximated as a slant surface with its far end slanted toward the frontoparallel plane. We hypothesize that the implicit slant surface reflects the intrinsic bias of the visual system and helps to define the perceptual space. Accordingly, we conducted two experiments in the dark to further elucidate the characteristics of the implicit slant surface. In the first experiment we measured the egocentric location of a dimly lit target on, or above, the ground, using the blind-walking – gesturing paradigm. Our results reveal that the judged target locations could be fitted by a line (surface), which indicates an intrinsic bias with a geographical slant of about 12.4°. In the second experiment, with an exocentric/relative-distance task, we measured the judged ratio of aspect ratio of a fluorescent L-shaped target. Using trigonometric analysis, we found that the judged ratio of aspect ratio can be accounted for by assuming that the L-shaped target was perceived on an implicit slant surface with an average geographical slant of 14.4°. That the data from the two experiments with different tasks can be fitted by implicit slant surfaces suggests that the intrinsic bias has a role in determining perceived space in the dark. The possible contribution of the intrinsic bias to representing the ground surface and its impact on space perception in the light environment are also discussed.

1 Introduction

Human observers can accurately judge the egocentric/absolute distance of a target on the continuous ground surface, up to a distance of roughly 20 m, in the light environment (see Loomis et al 1996 for a review). This ability has been attributed to the availability of various oculomotor and environmental visual information that serves as depth cues for the visual system, such as accommodation, convergence, height-in-the-field, perspective, texture gradient information, etc. Indeed, the question of the utility of these depth cues in space perception is indisputable and has been known for centuries (eg Cutting and Vishton 1995; Gibson 1950a, 1979; Sedgwick 1986; Wade 1998). Rather, much of the challenge we confront today is to uncover the computational steps involved in transforming the depth information into perceived space layout.

As for the height-in-the-field cue, also referred to as the angular declination below the horizon cue, Euclid (around 300 BC) was perhaps one of the first to document the idea that the angular declination information can be used by the visual system to obtain egocentric distance (Burton 1945; Wade 1998). In more recent times, a number of laboratories have further elaborated on the theoretical and empirical aspects of this

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classical idea (eg Epstein 1966; Gardner and Mon-Williams 2001; Gibson 1950a, 1979; Ooi et al 2001; Philbeck and Loomis 1997; Sedgwick 1986; Wallach and O'Leary 1982; B Wu et al 2004). For instance, in a two-prong approach, we (Ooi et al 2001) first used a pair of base-up prisms to optically increase the angular declination of a target, to show that it led to an underestimation of egocentric distance. Second, capitalizing on the observer's ability to adapt to prisms after prolonged viewing, we found that egocentric distance was overestimated upon removal of the base-up prisms. This is because the aftereffect of adapting to the base-up prisms is a lowered perceived eye level (the physical eye level is the projection line from the eyes to the horizon and is parallel to the flat ground surface). And since the angular declination is the angle between the eye level and the projection line to the target (figure 1a), a lowered perceived eye level has the effect of reducing the perceived angular declination. When the perceived angular declination is smaller, a target below the horizon is seen as further away, confirming that angular declination is a viable depth cue.

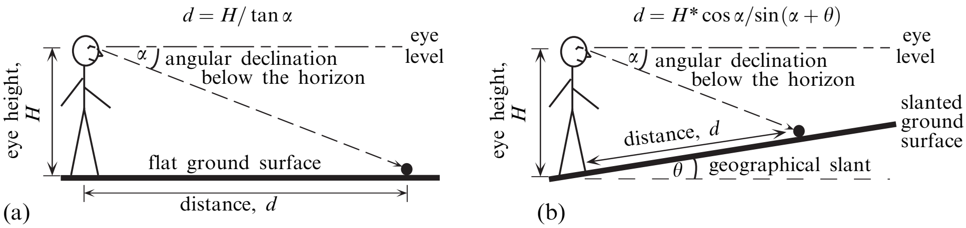


Figure 1. Illustrations of the trigonometric relationships that can be used to obtain the distance of a target on (a) a flat ground surface; (b) a slanted ground surface with a geographical slant of $\theta°$.

Figure 1a describes the trigonometric relationship from which the egocentric distance of a target on the flat ground surface, d, can be derived from the angular declination, α: $d = H/\tan\alpha$. For a slant floor surface with a geographical slant, θ, shown in figure 1b, the visual system can obtain egocentric distance according to the trigonometric relationship: $d = H\cos\alpha/\sin(\alpha + \theta)$. From these figures, it is clear that, if the visual system were to adopt the trigonometric computation, it also needs to correctly represent the three parameters in the equation, namely, the eye height, H, the angular declination, α, and the geographical slant of the ground surface, θ. Research has shown that of the three parameters all could be visually represented, with the eye height and angular declination usually remaining relatively accurate and constant, while the geographical slant being more prone to inaccuracy.

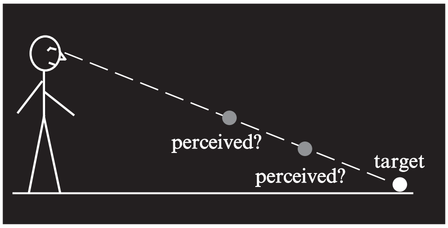
The eye height, H, is the vertical distance between the eye and feet on the level ground surface (figure 1). For most people, the eye height is within the vertical range of 2 m, which is a depth range where many studies have revealed that the near depth cues are most abundant and effective (for reviews, see Cutting and Vishton 1995; Sedgwick 1986). The visual system can reliably code the eye height by using the abundant near depth cues around the observer's feet on the ground surface. Consistent with this, we (Sinai et al 1998) found that when an observer stood on a ledge with a vertical distance of 2 m from the lower ground surface, he/she overestimated the eye height (the sum of eye-to-feet and feet-to-lower-ground-surface distances). We believe this is possibly because standing on the ledge puts the 'new' eye height beyond the effective range of the near depth cues on the lower ground surface. Finally, since the eye-to-feet distance is more or less constant in an adult and we normally walk/stand on a level ground surface, the visual system can use its stored information (memory) of the eye height and/or use the body senses information to establish the eye height when the near ground surface cues are not available (such as when in the dark) (Dixon et al 2000; Mark 1987; Warren and Whang 1987).

Computing angular declination, α, requires knowledge of both the retinal eccentricity of the target's image and the gaze direction. Since the angular declination is defined with reference to the eye level, it means that the eye level has to be reliably coded for accurate angular declination and egocentric-distance judgments. Indeed, as revealed by our studies (Ooi et al 2001; J Wu et al 2002, 2003, 2005), a change in the perceived eye level affects the angular declination and judged distance. Various researches have revealed that the visual system can obtain the eye level by relying on both the body senses and environmental visual information (Howard 1986; Matin and Li 1994, 1995; Ooi et al 2001; Sedgwick 1983, 1986; Stoper and Cohen 1986; J Wu et al 2002, 2003, 2005).

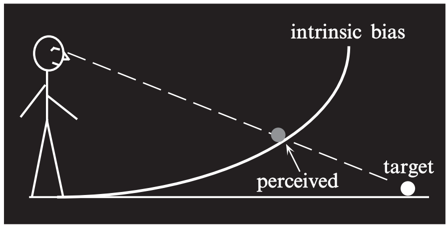
To represent the ground surface and its geographical slant, θ, the visual system can rely on a variety of depth cues on the ground surface. For the near ground-surface region in the vicinity of the observer ($< 2-3$ m), the visual system can derive the geographical slant using near depth cues such as accommodation, binocular disparity, and motion parallax. To represent the farther patches of the ground surface beyond $2-3$ m, the visual system depends mainly on the texture-gradient information on the ground surface (Gibson 1950a, 1979; Gibson and Cornsweet 1952; Purdy 1960; Sedgwick 1983, 1986). To form a global surface representation that includes both the near and farther regions of the ground, we have proposed that the visual system can employ a sequential surface-integration process (SSIP) (He et al 2004; B Wu et al 2004). The SSIP first represents the near ground surface, and then uses the near ground-surface representation as a template to integrate the local texture-gradient information of the farther surface patches to form an extended ground-surface representation. Thus, step-by-step, the visual system integrates the surface information from near to far to form a global ground-surface representation. Critical to the SSIP, is the initial representation of the near ground surface since it serves as a template for further processing. If its representation is inaccurate, say owing to insufficient near depth cues, then the subsequent far texture-surface representation, and consequently, the global surface representation will be inaccurate (He et al 2004; Sinai et al 1998; B Wu et al 2004).

Thus, given that the visual system can represent the eye height H, the angular declination α, and the ground surface θ—with the reliability of the representations dependent in part on the availability of depth cues—the case can be made for a trigonometric strategy for judging distance (figure 1). For a target on a continuous ground surface with ample depth cues in the light environment, the judged egocentric distance is accurate. But for a target in the dark, which is an extreme condition that deprives the visual system of visible depth cues from the surrounding, judged egocentric distance is inaccurate (eg Gogel and Tietz 1973; Ooi et al 2001; Philbeck and Loomis 1997; Philbeck et al 1997; B Wu et al 2000). Nevertheless, though inaccurate, studies have shown that the visual system can still implement the trigonometric strategy to obtain egocentric distance when the ground surface is not visible (Ooi et al 2001; Philbeck and Loomis 1997; B Wu et al 2000) (figure 2a). Our experiments have revealed that instead of using the physical ground surface (since it is not visible in the dark), the visual system relies on an implicit slant surface (Ooi et al 2001; B Wu et al 2000). For instance, a small dimly lit target located at an intermediate distance (beyond $2-3$ m) in the dark is represented at the intersection of its projection line from the eye to the target (angular declination) and the implicit surface (figure 2b). When the angular declination of the target is small, the target is represented as farther and higher, at a location defined by the intersection of the projection line and the implicit surface. These findings lead us to hypothesize that the implicit slant surface reflects an intrinsic bias of the visual system in influencing the representation of the ground surface, which plays an important role in computing egocentric distance.

Our first goal in the current study is to further elucidate the characteristics of the implicit surface (the intrinsic bias) and to determine the degree of slant of the implicit



(a)



(b)

Figure 2. (a) The uncertainty of judging the location of a dimly lit target that is placed on the floor in an otherwise dark room. (b) The perceived location of the dimly lit target is constrained by the angular declination of the target and the intrinsic bias of the visual system. The intrinsic bias is in the form of an implicit curved surface, which could be approximated as a slant surface. When placed in the intermediate distance range, the dimly lit target in the dark is perceived at the intersection of the projection line from the eye to the target and the implicit slant surface. Without the intrinsic bias, a light target located beyond the near distance range in the dark would be perceived at any position along its projection line from the eye, as shown in (a).

surface. Our second goal is to show, using a different task in the dark, that perceived exocentric distance depends also on the implicit surface. The following theoretical analysis outlines the trigonometric relationships between the exocentric distance and the implicit surface, which will be investigated in the second experiment.

1.1 *Theoretical background: The geographical slant of the implicit surface, η, and exocentric-distance judgment*

So far, the concept of the intrinsic bias has been developed from our studies with the use of egocentric-distance judgment task (Ooi et al 2001; B Wu et al 2000). Arguably, if the intrinsic bias is indeed an implicit slant surface in the dark, we should be able to prove that the implicit slant surface also affects a different space-perception task in the dark. To examine this, in experiment 2 in the current report we used an exocentric/relative-distance 'L-shaped' task, a task that is related to perceiving local surface shape. The L-shaped task is adapted from the one originally used by Loomis and Philbeck (1999). We performed the task in a dark room with two thin fluorescent stripes arranged at right angle to form an L shape. The observer was required to match the horizontal (width) and vertical (length/depth) limbs of the L-shaped target.

In tests in the dark, we predict that the L-shaped target that is placed on a flat surface (black surface in figure 3) will be perceived as if located on an implicit slant surface with a geographical slant η (gray surface in figure 3). We can test this prediction by measuring how observers match the width and the length/depth of the L-shaped target in the dark, and analyzing the data in terms of the ratio of the judged (perceived) aspect ratio to the physical aspect ratio of the L-shaped target (RAR).

As illustrated in figure 3, RAR is a function of the geographical slant η of the implicit surface. The L-shaped target on the flat surface (black surface) with length L and width W is represented on the intrinsic surface (gray surface) with a geographical slant η and is perceived with length l and width w. We can obtain the following relationship between RAR and η:

$$\mathrm{RAR} = \frac{l}{w} \Big/ \frac{L}{W} = \frac{H}{H\cos\eta + (D+L)\sin\eta}\,, \tag{1}$$

where H is the observer's eye height and D is the physical distance to the base of the L-shaped target from the observer (figure 3). To introduce the angular declination parameter α, we can rewrite equation (1) as:

$$\mathrm{RAR} = \frac{\sin(\alpha - \Delta\alpha)}{\sin(\alpha - \Delta\alpha + \eta)}\,. \tag{2}$$

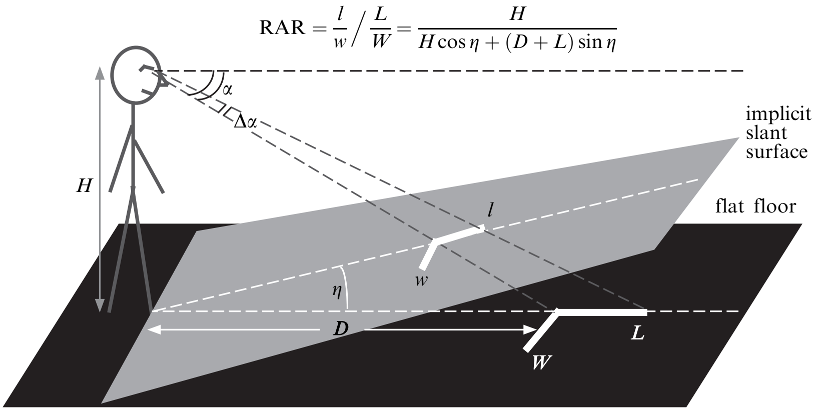


Figure 3. The visual representation of an L-shaped target tested in the dark. The intrinsic bias is approximated as a slant surface (gray trapezoid surface) with a geographical slant of η. The L-shaped target (white) on the flat floor surface (black surface) is represented as located on the slant surface, and the ratio of the judged (perceived) aspect ratio to the physical aspect ratio (RAR) is given by $(l/w)/(L/W)$. The uppercase L and W are, respectively, the physical length and width of the L-shaped target; and the lowercase l and w are, respectively, the perceived length and width of the L-shaped target. The trigonometric relationship between RAR and the geographical slant of the implicit surface, η, can be expressed as $\mathrm{RAR} = H/[H\cos\eta + (D+L)\sin\eta]$. H is the observer's eye height and D is the physical viewing distance from the observer to the base of the L-shaped target.

To test how RAR is affected by η, we consider the situation when $w = l$. This can be achieved in the experiment by keeping the width, W, of the L-shaped target constant, and adjusting its length, L, until the observer perceives that W and L are equal, ie when $w = l$. In this case, we can obtain the function RAR as:

$$\mathrm{RAR} = \frac{H - W\sin\eta}{H\cos\eta + D\sin\eta}\,. \tag{3}$$

In this paper, we first report our experiment in which we measured the egocentric distance of a target in the dark, tested over a larger spatial range than that used by Ooi et al (2001). This allows us to gain further understanding of the role of the intrinsic bias in space perception, and to obtain the geographical slant η of the implicit surface (figure 1). Second, we report our experiment testing the prediction that RAR is a function of η, as specified by equation (3). We predict that the derived geographical slant η from experiment 2, based on equation (3), will be comparable with the geographical slant η obtained from experiment 1.

Preliminary reports of this work have been presented in abstract forms (Ooi et al 2002; B Wu et al 2000).

2 Experiment 1: Judging target locations in the dark with the blind-walking – gesturing paradigm

Other than extending the maximum test distance from 5 m to 7.5 m, the blind-walking – gesturing paradigm used in this experiment was the same as the one described by Ooi et al (2001). This paradigm is similar to the more commonly used blind-walking paradigm, but with an additional task (gesturing) required of the observer. In the typical blind-walking paradigm, an observer first previews a target and judges its distance, and then walks blindly according to the remembered target distance. The distance traveled is taken as the judged horizontal distance, x, between the observer and the target (Elliot 1987; Loomis et al 1992, 1996; Rieser et al 1990; Sinai et al 1998; Thomson 1983).

In the blind-walking – gesturing paradigm, besides the judged horizontal distance x, the judged vertical height, y, of the target from the ground surface is measured as well. This is done by having the observer gesture the perceived height y of the target using his/her hand after finishing walking to the remembered target position x.

2.1 *Method*

2.1.1 *Observers.* Nine observers with informed consent and normal or corrected-to-normal vision participated in the experiment. Their physical eye heights were measured before the experiment. To familiarize the observers with the blind-walking task prior to the experiment, they were instructed to practice the task 5 – 10 times at various distances in the hallway outside the test room. After each practice trial, and to prevent the observer from having any feedback regarding the accuracy of his/her performance, the experimenter instructed the observer to keep the eyes closed while being escorted back to the starting location. Three of the nine observers had some prior experiences in performing visual psychophysical experiments, but none of them had any knowledge of the purpose of the current experiment.

2.1.2 *Stimuli.* The target was an internally illuminated red ping-pong ball (0.16 cd m^{-2}), which was encased in a contraption with an adjustable iris-diaphragm aperture. The experiment was conducted in a completely dark room, whose dimension (3×11 m) permitted us to place the test target at one of six different distances from the observer's feet and three different elevations/heights. The three test-target height conditions comprised placing the target on the flat floor surface, 0.5 m above the floor, and 0.5 m below the eye level. The six test-target distances were 1.5, 2.5, 3.75, 5.0, 6.25, and 7.5 m. At all viewing distances, the target subtended an angular size of 0.23 deg when measured at the eye level.

2.1.3 *Procedure.* The observer remained in a small well-lit waiting room in between trials. To begin a trial, he/she walked into the dark test room, and stepped onto two parallel rows of flat star-shaped fluorescent objects (1 mm thick) that were pasted on the floor. The purpose of the fluorescent stars was to position the observer at the correct starting location. This was achieved by ensuring that the front edges of the observer's shoes completely covered the stars as he/she stood steadily and upright on the same spot. When the observer was ready, the experimenter switched on the red light of the target that was placed at a randomly predetermined target location. To reduce the possibility of the observer experiencing the autokinetic effect, the experimenter used his hand to intermittently cover and uncover the target light at a rate of 0.5 – 1 Hz. The observer, in the meantime, judged and memorized the target distance and height. To ready himself/herself for walking, the observer held onto a guidance rope for safety with his/her right hand. (The rope was tied across the length of the room at a height about the observer's waist level.) When the observer was ready, he/she closed the eyes and asked the experimenter to remove the target. After doing this, the experimenter shook the guidance rope several times to signal the observer to start walking. The observer walked until he/she reached the remembered target location, then stood still, and indicated with the left hand the remembered target height. At this point, the observer kept his/her eyes closed as the experimenter marked the location where the observer stood on the floor, and measured the gestured height. This completed the trial, and the observer, still with eyes closed, was escorted to the waiting room, so that the experimenter could set up another target location for the next trial. No feedback was given to the observer regarding his/her performance. Also, music was played aloud during the trial to prevent possible acoustic clues to distance. Each target location was tested twice in a randomly predetermined order. The observer performed the experiment binocularly.

2.2 *Results*

The top and bottom rows of graphs in figure 4 show, respectively, the judged distance and judged height of the target as a function of the physical target viewing distance for the condition: (a) where the target was located on the floor, (b) where the target was 0.5 m above the floor, and (c) where the target was 0.5 m below the eye level. Regardless of the test-target heights, there are definite trends for the judgments of target distances and heights. For target-distance judgments, observers tend to overestimate distances of near targets and underestimate distances of far targets (top row graphs). And except for the targets on the floor that show increasing height overestimations with target distances, observers tend to underestimate the heights of near targets and overestimate the heights of far targets (bottom-row graphs). Overall, the data show trends similar to our previous findings (Ooi et al 2001; B Wu et al 2000).

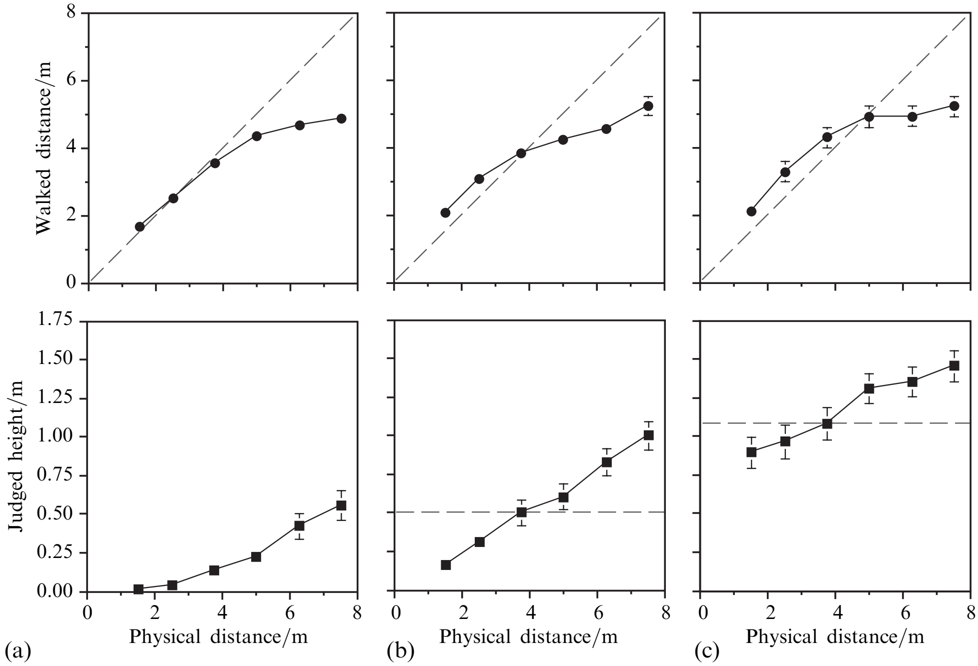


Figure 4. Averaged judged distance (top row graphs) and judged height (bottom row graphs) of a dimly lit target as a function of the physical viewing distance in the dark ($n = 9$). The dimly lit targets were placed at one of three different heights: (a) on the floor; (b) 0.5 m above the floor; (c) 0.5 m below the eye-level. Error bars represent ± 1 SE.

We replotted the data from figure 4 into figure 5 to provide a more direct comparison between the physical and judged target locations. To depict the judged target location, we took the averaged judged distance from figure 4 as the x coordinate and the averaged judged height as the y coordinate. We then plotted the x and y coordinates onto the graphs in figure 5: (a) for the target on the floor, (b) for the target 0.5 m above the floor, and (c) for the target 0.5 m below the eye level. Each judged target location (x, y coordinates) is shown with a black circular symbol; the physical target locations are shown on the same graphs with gray diamond symbols. Finally, to show the link between the physical and judged target locations, we drew a solid line to connect each set of gray diamond and black circular symbols. Effectively, this link shows us directly the perceived location of a target relative to its physical location.

Another advantage of the plots in figure 5 is that they permit us to draw projection lines (dashed line) from the eye (averaged eye height shown by an open circle on the

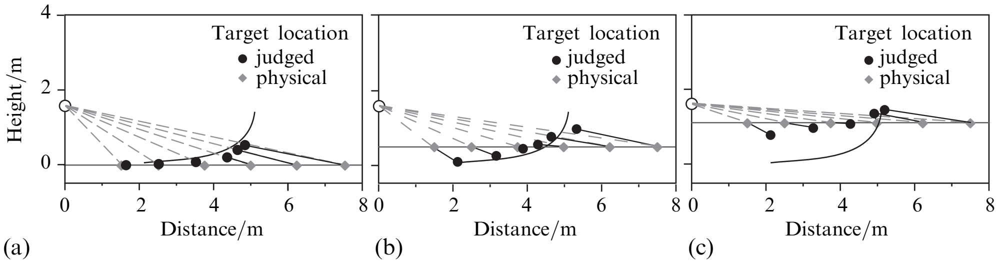


Figure 5. Displays of the averaged judged locations of a dimly lit target (filled circles) in the dark, for three height conditions: (a) on the floor; (b) 0.5 m above the floor; (c) 0.5 m below the eye-level. The judged target locations are based on the averaged judged distances, x, and judged heights, y, in figure 4. The open circle drawn on each y axis depicts the averaged eye height of the observers. The gray diamond symbols represent the physical target locations; they are connected to the eye height by dashed lines (projection lines) and connected to their corresponding judged locations by solid lines. Notice that the dashed lines are generally continuous with the straight solid lines. That is, the data reveal that each set of judged and physical target locations falls along the same direction, suggesting an accurate perception of target direction. In both (a) and (b), the judged locations can be fitted by the same black curve, which represents the implicit slant surface.

y axis) to the respective physical target locations. Doing so allows one to immediately notice that each solid line connecting a given set of physical and judged target locations is more or less continuous with the straight projection line to the same physical target location. This indicates that the judged angular declination, ie the judged direction of a target, is basically accurate in the dark.

To illustrate the accuracy of the perceived angular declination, we next correlated our observers' judged angular declination with the physical angular declination for each target location from all three height conditions. The scatter plot is shown in figure 6, which consists of 162 data points (9 observers $\times$ 18 target locations). Overall, the data are evenly distributed about the diagonal line, and can be approximated with a regression line with a linear equation $y = 0.999x - 0.902$ ($R^2 = 0.932$; the least-squares criterion). This underscores the notion that judged angular declination is more or less veridical.

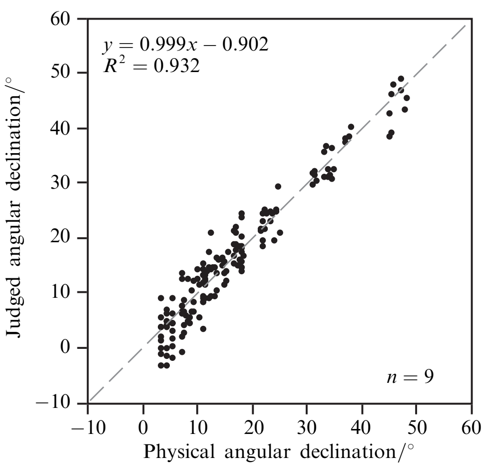


Figure 6. Scatter plot of the judged angular declination of the dimly lit target as a function of the physical angular declination of the target for all three height conditions (9 observers $\times$ 18 target locations). The data are distributed about the diagonal line indicating that the judged angular declination of the dimly lit target in the dark is more or less veridical.

2.3 *Analysis and discussion*

We can derive two major conclusions from our results. One, perceived object location in the dark is inaccurate because of the absence of visible depth cues on the ground. Two, and most remarkably, there is an order to the perceived location inaccuracies. This is perhaps best depicted by figure 5, which shows that the misperception of target locations was not due to errors in judging the target directions but rather to judging their distances. It also implies that the veridical direction percept plays a role in constraining the shape of our perceptual space in the dark, and possibly even in the light environment.

Consider the task of judging the location of a target on the ground in the intermediate distance in the dark, as shown in figure 7a. Since this task is similar to our task in experiment 1, we now know that the target distance is underestimated even when its direction is correctly perceived. Accordingly, figures 7b and 7c each depicts the perceived target distance to be nearer to the observer than the physical target distance. But only figure 7b correctly depicts the perceived direction of the target, which is in the same direction as that of the physical target. In effect, figure 7b indicates that a target on a flat floor surface (gray line) is perceived as if it were located on a slant floor surface (black line). Figure 7c, while having the perceived distance from the eye to the target the same as in figure 7b, has the perceived angular declination of the target larger than the physical angular declination. The latter is inconsistent with our finding that perceived direction is correct. Therefore, we can surmise from figure 7 that the perceived locations of targets in the dark are constrained by their perceived directions. And from the profile of the perceived targets as a function of viewing distances in figure 5, we can further surmise that targets at various distances in the dark are perceived as if they were placed on a surface whose far end was approximately slanted towards the observer's frontoparallel plane. This surface is likely to be similar to the slant surface (black line) depicted in figure 7b, and is unlikely to be the flat and compressed surface (black line) in figure 7c. Such an analysis and the results thus far confirm our proposal that the slant surface is the visual system's default, or intrinsic bias, in representing the ground surface when visible depth cues on the ground are absent.

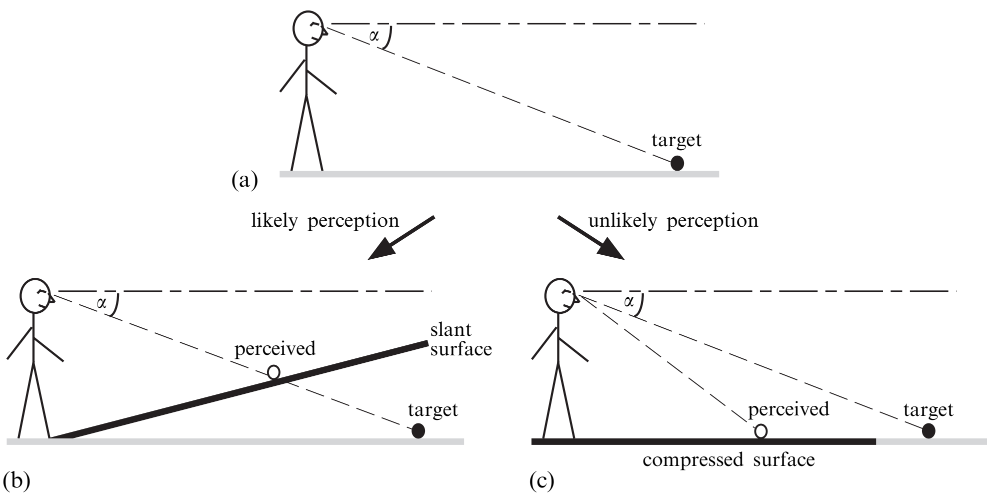


Figure 7. The veridical coding of the target direction serves as a constraint for the construction of the perceptual space in the dark. (a) A dimly lit target placed on the flat floor surface (gray line) in the intermediate distance range subtends an angular declination α. Given that its judged distance will be underestimated, its location (distance + height) could be perceived according to the scheme in (b) or (c). (b) The judged target distance is underestimated, and in keeping with the veridical direction constraint; its perceived height is raised above the floor. This suggests that the target is perceived as if it were laid on an implicit slant surface (black line), instead of on the flat floor surface (gray line). (c) The judged target distance is underestimated and its perceived height is on the flat floor. This suggests that the target is perceived on a flat floor with a compressed surface (black line) (note: the black line is continuous with the gray line of the flat floor, but shortened to represent compression). This scheme is incorrect because it has the judged angular declination of the target larger than the physical angular declination, in violation of the veridical direction constraint.

The idea of an intrinsic bias not only provides a basis for a trigonometric strategy for the visual computation of distance, but also helps describe the perceptual space.

To further describe the intrinsic bias of the visual system, we drew a curve (best fit by the eye) to represent the putative intrinsic bias and fitted it onto the data in all three graphs of figure 5. Although there are some systematic departures from the curve, the data generally fit the curve reasonably well in plots (a) and (b) (for targets on the floor and 0.5 m above the floor). Noticeably, the data for the targets on the floor are slightly below the curve, whereas the data for the targets 0.5 m above the floor are slightly above. A possible explanation for this is that, in our study, the observers were not restrained from moving their heads during the experiment. Thus motion perspective might have contributed slightly to the systematic departures of the data from the curve.

The fit of the curve to the data in figure 5c (targets 0.5 m below the eye level) is less good. In fact, the data points for the judged target locations of targets nearer to the eyes are quite far from the curve. We suspect it is likely that, within this close distance range, near depth cues such as binocular disparity, motion parallax, etc, are still effective and thus carry a relatively larger weight than the intrinsic bias in determining the perceived target locations.

Finally, to quantify the intrinsic bias, we applied a plane approximation (figure 3) to the pooled data of the judged target locations for the conditions where the targets were on the floor and 0.5 m above the floor (figures 5a and 5b). We employed the least-squares criterion method to obtain the regression line ($y = 0.218x - 0.408$, $R^2 = 0.656$) and the estimated geographical slant ($\eta = 12.4°$). The current estimate of the geographical slant is compatible with the one we obtained in our previous study ($\eta = 13.5°$) under a similar viewing condition (Ooi et al 2001).

3 Experiment 2: Judging the RAR of an L-shaped target in the dark

On the basis of measuring judged locations of dimly lit targets in the dark, experiment 1 showed that targets are perceived as if they were laid on an implicit slant surface whose geographical slant was about 12.4°. This is consistent with our proposal that the slant surface is the intrinsic bias of the visual system for coding target location in the intermediate distance when the ground surface is not visible in the dark. It is as if the implicit surface in the dark acted as a reference frame, and had a role similar to the ground-surface representation in the light environment for coding object locations. Accordingly, in experiment 2 we tested the prediction that the implicit slant surface will affect the performance in an exocentric distance task in the dark in a similar way that it affected judged egocentric target locations in experiment 1.

3.1 *Method*

3.1.1 *Observers.* Eleven observers with informed consent and one author (ZJH), all with normal or corrected-to-normal vision, participated in the experiment. They all had some prior experiences in performing visual psychophysical experiments, but none, except ZJH, knew the purpose of the current study. These observers did not participate in experiment 1. Their eye heights were measured before the experiment. They were instructed on the criterion for matching the two limbs of the L-shaped target with an instruction that was similar to that used by Loomis and Philbeck (1999). In addition, we emphasized to the observers that they should not try to match the two limbs of the L-shaped target on the basis of the retinal image sizes, since our goal was to measure the observer's perceived distance in 3-D space. The majority of our observers easily understood the difference between retinal image size and physical target size. The observers were given some practice trials (5 – 10 at various distances) in performing the L-shaped task either in the dark (test room) or light (hallway).

3.1.2 *Stimuli.* The experiment was conducted in a dark room. The L-shaped targets were produced with green fluorescent stripes (width = 2.54 cm) arranged at right angle. The intensity of the fluorescent stripes was bright enough for the observers to see, but not so intense as to cause the fluorescence to make the surrounding areas visible to the observers. Three sets of L-shaped targets with variable lengths and fixed widths ($W = 0.2$, 0.3, and 0.4 m) were used. Of the three target widths, only the 0.3 m L-shaped target was used as the test target; the other two targets were used in catch trials. The catch trials comprised one third of the total 30 trials, and were randomly interleaved with the test trials. During the experiment, the L-shaped target was laid flatly, either on the flat floor or on a box with a flat surface that was 0.5 m above the floor. The base of the L-shaped target, which was nearest to the observer, was used as a reference to measure the viewing distance between the L-shaped target and the observer. The viewing distances were 2.5, 3.75, 5.0, 6.25, and 7.5 m. In all, with the two test-height conditions (floor and 0.5 m above), the test target ($W = 0.3$ m) was placed at 10 different locations, with each location tested twice.

3.1.3 *Procedure.* The observer stayed in the well-lit waiting room in between trials, and entered the dark room only when instructed. As in experiment 1, the observer stepped onto the two rows of fluorescent stars that helped to position him/her. The procedures for measuring RAR of the L-shaped target was similar to the one used by Loomis and Philbeck (1999). The observer performed the experiment binocularly. During the trial, the observer stood upright and viewed the L-shaped target from one of the five predetermined viewing distances. The observer imagined that he/she had walked up to the L-shaped target and looked down directly at it. From this imagined vantage point, he/she then judged if the width (fixed horizontal limb) and length (variable vertical limb) of the L-shaped target match. If they did not, the observer instructed the experimenter to adjust the length of the L-shaped target accordingly. A thick black cardboard was used to cover/uncover the length of the L-shaped target during the adjustment. The observer closed the eyes when he/she was satisfied with the match, and was escorted back to the waiting room. This allowed the experimenter to measure and record the length set by the observer, and to prepare for the next trial. No feedback regarding performance was given to the observer during the experiment.

3.2 *Results*

Figure 8a shows the averaged results for the test target ($W = 30$ cm) by expressing 1/RAR as a function of the viewing distance of the L-shaped target. [We use 1/RAR instead of RAR here because our equation (3) predicts a linear relationship between 1/RAR and distance D.] Clearly, for all distances tested, and whether the target was on the floor (circles) or 0.5 m above the floor (squares), 1/RAR is larger than 1. That is, $L > W$, indicating an underestimation of the length L, or depth, of the L-shaped target relative to its width W (Loomis et al 1992, 2002; Loomis and Philbeck 1999; Norman et al 1996; Toye 1986; Wagner 1985; B Wu et al 2004). 1/RAR increases with the distance of the L-shaped target ($F_{4,44} = 93.8$, $p < 0.001$; 2-way ANOVA with repeated measures). Also, 1/RAR was larger when the L-shaped targets were located 0.5 m above the floor than when located on the floor ($F_{1,11} = 33.67$, $p < 0.001$; $F_{4,44} = 3.781$, $p < 0.025$; 2-way ANOVA with repeated measures).

3.3 *Analysis and discussion*

Recall that equation (2) implies that RAR is a function of the angular declination α, rather than the viewing distance of the L-shaped target. Therefore, in figure 8b we replotted the 1/RAR data in figure 8a as a function of α, instead of the viewing distance. Clearly, the two sets of data from the two different height conditions are now closer together, which underscores the prediction of equation (2). Our finding is consistent

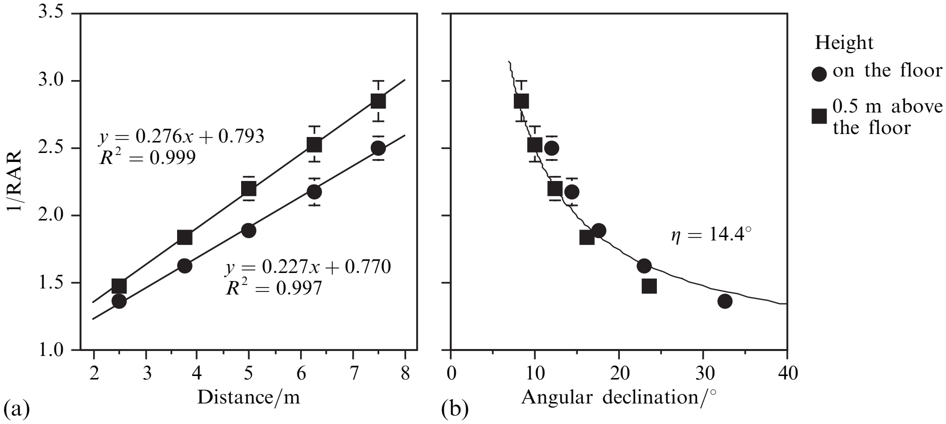


Figure 8. (a) The averaged 1/RAR data as a function of the physical viewing distance of the L-shaped target ($n = 12$), for the target on the floor (circles) and 0.5 m above the floor (squares) conditions. The two lines fitting the data, one for each condition, are regression lines obtained by the least-squares criterion. (b) The averaged 1/RAR data replotted as a function of the angular declination of the L-shaped target. The two sets of data from the two height conditions almost merge, indicating that RAR depends on the angular declination. These data are fitted by a black curve obtained by the least-squares criterion. The curve is based on equation (2), and the best fit is found when the geographical slant, η, is 14.4°. Error bars represent ±1 SE.

with the studies by Loomis and his colleagues (Loomis and Philbeck 1999; Loomis et al 2002) who demonstrated that, in the light environment, RAR of an L-shaped target is a function of the optical slant. The optical slant is the angle between the projection line from the eye to the base of the L-shaped target and the surface supporting the L-shaped target (Sedgwick 1983). [Note that this definition of the optical slant differs from that used by Loomis and Philbeck (1999), who defined it as the angle between the projection line and the surface normal to the L-shaped target.] And, since the L-shaped target was laid on flat surfaces in our experiment, the angular declination and optical slant have the same value [please refer to the Appendix for a generalization of equation (2) to the optical slant of the L-shaped target].

Finally, to determine if the data in figure 8b can be predicted from equation (3), we pooled the L-shaped data from both height conditions to obtain the geographical slant η of the implicit slant surface. Using the least-squares criterion, we found η to be 14.4°. Then, using this value and equation (2), we drew the black curve in figure 8b. Clearly, the curve fits the data well, indicating that the performance in the L-shaped task can be related to an implicit slant surface.

Recall that, in experiment 1, the geographical slant of the implicit slant surface obtained from pooling the data from both the floor and 0.5 m above the floor conditions was 12.4°. Thus, while the geographical slants derived from both experiments 1 and 2, 12.4° and 14.4° respectively, are quite close, there is a noticeable difference of 2.0°. We suspect this difference stems in part from using different groups of observers in the two experiments, and from the different task demands/limitations of each experiment.

Note, in particular, our data for the target on the floor condition of experiment 1 (figure 5a). Unlike the other two conditions in figures 5b and 5c (targets 0.5 m above the floor and 0.5 m below the eye level), the judged distances of the two nearest targets in figure 5a were not much overestimated. This finding is contrary to the well-known observation that distances of near targets in the dark tend to be overestimated (Gogel and Tietz 1973; Philbeck and Loomis 1997). Moreover, since perceived target direction is veridical, the two nearest targets for the floor condition could have been perceived as farther and lower than the floor. But, of course, our observers were not able to gesture the targets below the floor, even if they had perceived the targets to be so. For, one, they knew that the targets could not have been placed below the floor, and, two, it was impossible for them to gesture with their hands below the solid floor surface. For these reasons, if based on our data from the floor condition alone (and using the least-squares criterion), the derived geographical slant of the implicit surface would be small. Consequently, when we calculated the geographical slant of the implicit surface by pooling the data from both the floor condition and the 0.5 m above the floor condition, a value of η smaller than its 'true' value would be found. To support this premise, we have calculated the geographical slant of the implicit surface solely on the basis of the data from the 0.5 m above the floor condition, and found η to be 15.1°. This value is closer to the 14.4° value obtained from the L-shaped experiment (figure 8b).

Clearly, the current findings reveal that the intrinsic bias affects both judged target location (experiment 1) and surface orientation (experiment 2) in the dark. However, we also wish to add some cautionary notes to our favored conclusion. It could be argued that the agreement between the two computed geographical slants from both experiments could be mere coincidence. First, this is because the observed (computed) geographical slants were approximations (of the intrinsic bias), since we assume that the intrinsic bias takes the form of a slant plane with a constant geographical slant But, in actuality, our entire data set (figure 5) appears to be better described by a curved surface whose geographical slant increases with distance. Second, we are reminded that both perceived object location and surface orientation are determined by the intrinsic bias of the visual system as well as the extrinsic depth cues (Ooi et al 2001; Sinai et al 1998; B Wu et al 2004). It is likely that the geographical slant computed from the data in experiment 1 more closely reveals the intrinsic bias of the visual system since few, if any, extrinsic depth cues existed (the target in the intermediate distance range was a spot of light that carried little depth information). In contrast, the geographical slant computed from the data in experiment 2 might reflect the contribution of both the intrinsic bias and local binocular disparity information. This is because our observers performed the exocentric task with binocular viewing.

4 General discussion

Our previous studies showed that, when the ground surface is not visible in the dark, the visual system codes the location of a dimly lit target on the basis of its angular declination and an intrinsic bias (implicit slant surface). The intrinsic bias acts as a reference frame for space perception in the dark, just as the ground surface representation does in the light environment (Ooi et al 2001; B Wu et al 2000). In the current study we further investigated the nature of the intrinsic bias by using two different types of distance judgment tasks (egocentric versus exocentric distance tasks).

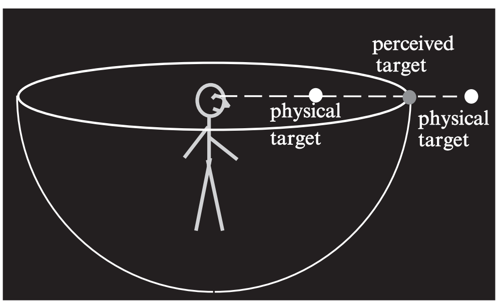
In the first experiment we used an egocentric distance judgment task that required observers to judge the location (distance and height) of a small spot of dimly lit target. This task was the same as the task used in our previous studies (Ooi et al 2001; B Wu et al 2000). However, the present experiment substantially extended the testing, which allows us to more precisely analyze the behavior of the visual system in the dark. Confirming our earlier findings, we first revealed that, although the observers made errors in judging the target location in the dark, the judged direction remains correct, suggesting a veridical coding of direction. Second, our data analysis demonstrates that targets in the dark are perceived as if they were located on an implicit slant surface, with an estimated geographical slant of about 15° (this value excludes the consideration of the targets on the floor, see the discussion in section 3.3).

In the second experiment we used an exocentric distance (relative depth) judgment task that required observers to match the width (in the frontoparallel plane) and length (in depth) of an L-shaped target. Similar to previous observations made in the light environment (Loomis and Philbeck 1999; Loomis et al 2002), we found that in the dark the RAR of the L-shaped target is a function of the optical slant (equivalent to the angular declination in our experiment). In addition, our data analysis shows that the observers performed as if they perceived the L-shaped target lying on an implicit slant surface with an estimated geographical slant of about 14°. This value is quite similar to that found in the first experiment. Thus, it suggests that an intrinsic bias affects both egocentric and exocentric distance perception.

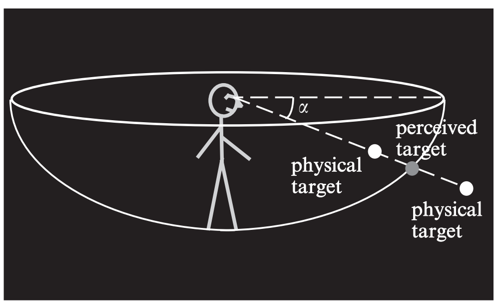
Overall, our experiments provide evidence of an implicit slant surface that reflects the intrinsic bias or internal state of the visual system. The implicit slant surface plays a similar role as the ground surface representation in the light environment, in contributing to the trigonometric computation of distance in the dark. Without the intrinsic bias, a light target located beyond the near distance range in the dark would be perceived at any position along its projection line from the eye. Furthermore, the finding of a veridical coding of target direction suggests that it serves as an important constraint for constructing one's perceptual space.

4.1 *The intrinsic bias and the specific distance tendency*

The notion that the visual system has an intrinsic bias in space perception in the dark is closely related to the idea advanced by Gogel and his colleagues in a series of studies (eg Gogel 1969; Gogel and Tietz 1973, 1979). They proposed a 'specific distance tendency' principle, to account for the observation that the perceived distance of a point-of-light target placed in the intermediate distance in the dark always tends to a fixed 'specific' distance. Even though their observation was based on experiments with targets located at the eye level—along a single visual direction—an implicit assumption has often been made that the specific-distance-tendency principle applies to targets along any visual direction. As such, whether the 'specific distance' has the same value for all other directions was not questioned. In this context, our current and previous studies (Ooi et al 2001; B Wu et al 2000) provide an extension of the important work of Gogel and his colleagues, by demonstrating that the specific-distance tendency is a function of the angular declination. Our study suggests that, had the specific-distance tendency been the same for all angular declinations—which it is not, the profile of the specific-distance tendency in 3-D space would have been a sphere with its center located at the eye (figure 9a). Instead, because the specific-distance tendency varies with different angular declinations, we propose that the profile of the specific-distance tendency in 3-D space is a conicoid-like surface (figure 9b).



(a)



(b)

Figure 9. (a) Illustration of a hypothetical perceptual space where the specific-distance tendency is a constant value for all target directions. It predicts that a target in the intermediate distance range will be perceived on a surface of an implicit sphere centered at the eye. (b) Illustration of a hypothetical perceptual space where the specific-distance tendency varies with the target angular declination. It predicts that a target in the intermediate distance range will be perceived on an implicit conicoid-like surface.

That the intrinsic bias takes the form of a conicoid-like surface rather than a spherical surface can be related to the biological significance of the ground surface in human space perception (Gibson 1950a, 1979). We are also aware, however, that the ground surface could not be the sole factor influencing the shape of the intrinsic bias of the visual system. Otherwise, one would expect the implicit surface to be as flat as the typical ground surface.

The biological significance of the ground surface in human perception has also been observed with regard to binocular depth perception (Breitmeyer et al 1975; Helmholtz 1867/1962; McCarley and He 2000; Nakayama 1977; Tyler 1991). For example, when one fixates at the horizon in the far infinity, the vertical horopter coincides with the ground surface beneath one's feet. This, presumably, facilitates the detection of objects on the ground surface. The representation of the vertical horopter can be achieved through the horizontal shear of the vertical meridians in the two retinas (Nakayama 1977; Tyler 1991).

The implicit surface for space perception in the intermediate distance, as reported in the current study, is probably mediated by a different neurophysiological mechanism from that for the vertical horopter. This is because the implicit surface is mainly responsible for space perception in the intermediate distance range; and, in fact, it has been shown that judged egocentric distance in the dark is similar under binocular and monocular viewing conditions (Philbeck and Loomis 1997; B Wu et al 2000). Moreover, the observers in the space perception tasks are not required to maintain eye fixation at a fixed position, unlike in measurements of the vertical horopter. In fact, a future experiment would be to investigate whether gaze direction affects the implicit surface as it does the vertical horopter. In our experiments above, eye movements were not controlled and the observers probably reflexively fixated at the dimly lit target while judging its location. The future experiment could test the observer in a monocular viewing condition that dissociates the gaze and target location. For example, one can ask the observer to maintain gaze at the primary position by fixating straight ahead as if looking to the far infinity, while judging the location of a target that is placed at some other angular declination. Such an experiment will allow one to determine if the judged target location is the same as when fixation is not restricted while making the judgment (as in the current study). If the judged location is the same, this would indicate that the visual system has a constant implicit slant surface that does not change with gaze direction.

4.2 *The intrinsic bias, optical slant, and frontal tendency*

Figure 3 and equation (3) predict that the geographical slant of the implicit surface can affect the judged RAR of the L-shaped target on the floor. Our results and data analysis of experiment 2 are consistent with this prediction (figure 8). Figure 3 also predicts that the intrinsic bias contributes to the perceived optical slant of the L-shaped target (the perceived optical slant = physical optical slant + the geographical slant of the implicit surface). This suggests that the L-shaped target should be seen as slanted toward the frontoparallel plane (frontal tendency). Indeed, we noticed the slant appearance of the L-shaped targets during our experiment even though they were placed on flat surfaces. It would be an interesting future experiment to quantitatively measure the perceived slant of the L-shaped target in the dark to determine the impact of the intrinsic bias on slant perception. There is precedence for this line of thinking, since studies have shown a link between perceived surface slant and perceived surface shape (Beck and Gibson 1955; Kaiser 1967; Massaro 1973). Furthermore, the L-shaped task to some extent can be considered as a shape-judgment task because it requires one to match the width and length of the target.

Does the intrinsic bias affect perceived surface slant in the light environment as well? In theory, the visual system can derive the optical slant of a patch of homogeneous-texture surface from the local texture-gradient information at that location (Gibson 1950a; Gibson and Cornsweet 1952; Purdy 1960; Sedgwick 1986). For example, for a surface with a texture gradient of angular size G_a, the optical slant will be defined by $\frac{1}{3}\operatorname{arccot} G_a$ (Purdy 1960; Sedgwick 1986). Consistent with this, but with varying degrees of accuracies (or inaccuracies), a number of studies have demonstrated that human observers can rely on the texture-gradient information to judge the surface slant (Braunstein 1968; Clark et al 1956; Eriksson 1964; Flock 1964; Freeman 1956; Gibson 1950b; Knill 1998). The noted inaccuracies, we propose, could be accounted for in part by the weighted contribution of the intrinsic bias to the surface slant computation, in addition to the contribution of texture-gradient information. In other words, the intrinsic bias of the visual system is usually masked in the full-cue light environment, and it exerts little or no influence unless the extrinsic depth cues are inadequate or unavailable for representing surfaces. The two observations below support this proposal.

First a number of studies in the past have demonstrated that observers could perceive the surface slant of an isolated texture surface on the basis of its texture-gradient information. However, the perceived slant with respect to the slant specified by the texture-gradient information is inaccurate (Braunstein 1968; Clark et al 1956; Freeman 1956; Gibson 1950b). More specifically, the perceived slant of the texture surface is biased towards the frontoparallel plane (frontal tendency). Notably, this slant bias is in the same direction as the intrinsic bias. Furthermore, the frontal tendency becomes stronger as the texture-gradient information becomes weaker, eg when one uses a regular texture surface as opposed to an irregular texture surface (Flock 1964; Gibson 1950b).

Second, in concert with the observation of a frontal tendency in perceiving the slant of a texture surface, the judged RAR of the L-shaped target on the ground is smaller than unity in the light environment (He et al 2004; Loomis et al 2002; Loomis and Philbeck 1999; Ooi et al 2004; B Wu et al 2004). For instance, we recently found that when an observer views the L-shaped target through a pair of goggles with a small aperture that restricts his/her field of view, RAR is reduced (B Wu et al 2004). This is because the limited visual field of view of the texture surface not only reduces the amount of texture-gradient information but also prevents the visual system from having access to the near depth information to form an accurate ground-surface representation. This effectively reduces the available visual cues and thus forces the visual system to rely more on the intrinsic bias to represent the slant of the local surface area supporting the L-shaped target. Hence, this leads to a smaller RAR, ie a stronger frontal tendency. In fact, RAR is even smaller when we use a smaller-size aperture to further restrict the available depth cues. This finding is also consistent with the observation that the frontal tendency increases when one decreases the size of an aperture through which the observer views a textured surface to judge its slant (Eriksson 1964; Flock et al 1966).

4.3 *On the relationship between the egocentric and exocentric distance judgments*

In the light environment with ample depth cues, observers can accurately judge the egocentric distance in a blind-walking task. Yet, even in the light environment, they make substantial errors in judging both the relative depth between two targets and RAR of a target on the ground (Amorim et al 1998; Loomis et al 1992, 2002; Loomis and Philbeck 1999; B Wu et al 2004). Several hypotheses based on a perceptual-action dissociation or on the involvement of different perceptual computational processes, etc, have been proposed to explain this difference between the absolute and relative distance performances (eg Amorim et al 1998; Beusmans 1998; Loomis et al 1992, 2002;

Vishton et al 1999; Wraga et al 2000). Our findings in this and a previous study (He et al 2004) suggest another possible hypothesis that is based on how information is selected for representing the ground surface.

Our previous studies (He et al 2004; B Wu et al 2004) showed that the accuracy of the global ground-surface representation in the light environment depends on how and where the visual system selects depth information on the ground surface. An accurate ground-surface representation is formed when the visual system is able to attend to and sample a wide expanse of the continuous ground surface, and when it is able to integrate depth information from the near and far ground-surface regions. Thus, it is possible that performance on an egocentric-distance task in the light environment is more accurate because the nature of the task compels the observer to scan a relatively large ground-surface area between himself/herself and the target. Doing so allows the ground surface to be more accurately represented, and consequently permits a more accurate derivation of distance based on the trigonometric strategy (see figure 1).

On the other hand, in the relative-distance (exocentric) task such as the L-shaped task, the observer mainly attends to a smaller area of ground surface that supports the L-shaped target. Thus, ground-surface representation in the light environment is mainly based on the local texture information in the small ground area surrounding the L-shaped target, and less on the near depth information or the global texture information. Lacking adequate depth information, the visual system resorts to representing the global ground surface with a relatively larger influence from the intrinsic bias. This means that the geographical slant of the represented ground surface is more slanted with its far end toward the frontoparallel plane, ie increased η. And, as shown by equation (3), RAR becomes smaller as η increases.

But considerations pertaining to the selection of environmental depth information, and how they affect the ground-surface representation no longer apply when the egocentric-distance and exocentric-distance tasks are performed in the dark. As the current study indicates, our visual system depends on the implicit slant surface (intrinsic bias) that acts as a reference frame for space perception in the dark. Recall that our two experiments revealed that the geographical slant of the implicit surface in either the egocentric-distance or exocentric-distance task was quite similar ($14° - 15°$). This means that the measured outcomes of the two tasks should be comparable as well, since both are related to the geographical slant of the implicit slant surface [see figure 1 and equation (3)]. In other words, the vastly different outcomes of the egocentric-distance and exocentric-distance tasks found in the light environment (Loomis et al 1992, 2002; Loomis and Philbeck 1999; B Wu et al 2004) can be partially, if not entirely, attributed to how the ground surface is represented. An egocentric-distance task in the light environment permits a more accurate representation of the ground surface, leading to a more accurate distance perception, in contrast to an exocentric-distance task. Overall, this discussion underscores the importance of the accurate representation of the ground surface to serve as a reference frame for distance perception (Feria et al 2003; Gibson 1950a, 1979; He et al 2004; Loomis et al 2002; Meng and Sedgwick 2001, 2002; Sedgwick 1986; Sinai et al 1998; B Wu et al 2002, 2004).

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References

Amorim M-A, Loomis J M, Fukusima S S, 1998 "Reproduction of object shape is more accurate without the continued availability of visual information" *Perception* **27** 69 – 86

Beck J, Gibson J J, 1955 "The relation of apparent shape to apparent slant in the perception of objects" *Journal of Experimental Psychology* **50** 125 – 133

Beusmans J M H, 1998 "Optic flow and the metric of the visual ground plane" *Vision Research* **38** 1153 – 1170

Braunstein M L, 1968 "Motion and texture as sources of slant information" *Journal of Experimental Psychology* **78** 247 – 253

Breitmeyer B, Julesz B, Kropfl W, 1975 "Dynamic random-dot stereograms reveal up – down anisotropy and left – right isotropy between cortical hemifields" *Nature* **187** 269 – 270

Burton H E, 1945 "The optics of Euclid" *Journal of the Optical Society of America* **35** 357 – 372

Clark W C, Smith A H, Rabe A, 1956 "The interaction of surface texture, outline gradient, and ground in the perception of slant" *Canadian Journal of Psychology* **10** 1 – 8

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 *Handbook of Perception and Cognition: Perception of Space and Motion* Eds W Epstein, S Rogers, volume 5 (San Diego, CA: Academic Press) pp 69 – 117

Dixon M W, Wraga M, Proffitt D R, Williams G C, 2000 "Eye height scaling of absolute size in immersive and nonimmersive displays" *Journal of Experimental Psychology: Human Perception and Performance* **26** 582 – 593

Elliot 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

Epstein W, 1966 "Perceived depth as a function of relative height under three background conditions" *Journal of Experimental Psychology* **72** 335 – 338

Eriksson E S, 1964 "Monocular slant perception and the texture gradient concept" *Scandinavian Journal of Psychology* **5** 123 – 128

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

Flock H R, 1964 "A possible optical basis for monocular slant perception" *Psychological Review* **71** 380 – 391

Flock H R, Tennet J, Graves D, 1966 "Depth information in single triangles and arrays of triangles" *Psychonomic Science* **6** 291 – 292

Freeman R B Jr, 1956 "Effect of size on visual slant" *Psychological Review* **72** 501 – 504

Gardner P L, Mon-Williams M, 2001 "Vertical gaze angle: absolute height-in-scene information for the programming of prehension" *Experimental Brain Research* **136** 379 – 385

Gibson J J, 1950a *The Perception of the Visual World* (Boston, MA: Houghton Mifflin)

Gibson J J, 1950b "The perception of visual surfaces" *American Journal of Psychology* **63** 367 – 384

Gibson J J, 1979 *The Ecological Approach to Visual Perception* (Hillsdale, NJ: Lawrence Erlbaum Associates)

Gibson J J, Cornsweet J, 1952 "The perceived slant of visual surfaces—optical and geographical" *Journal of Experimental Psychology* **44** 11 – 15

Gogel W C, 1969 "The sensing of retinal size" *Vision Research* **9** 1079 – 1094

Gogel W C, Tietz J D, 1973 "Absolute motion parallax and the specific distance tendency" *Perception & Psychophysics* **13** 284 – 292

Gogel W C, Tietz J D, 1979 "A comparison of oculomotor and motion parallax cues of egocentric distance" *Vision Research* **19** 1161 – 1170

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

Helmholtz H von, 1867/1962 *Treatise on Physiological Optics* volume 3 (New York: Dover, 1962); English translation by J P C Southall for the Optical Society of America (1925) from the 3rd German edition of *Handbuch der physiologischen Optik* (first published in 1867, Leipzig: Voss)

Howard I P, 1986 "The perception of posture, self motion, and the visual vertical", in *Handbook of Perception and Human Performance* Eds K Boff, L Kaufman, J Thomas (New York: John Wiley) pp 1 – 62

Kaiser P, 1967 "Perceived shape and its dependence on perceived slant" *Journal of Experimental Psychology* **75** 345 – 353

Knill D C, 1998 "Surface orientation from texture: Ideal observers, generic observers and the information content of texture cues" *Vision Research* **38** 1655 – 1682

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

McCarley J S, He Z J, 2000 "Asymmetry in 3-D perceptual organization: ground-like surface superior to ceiling-like surface" *Perception & Psychophysics* **62** 540 – 549

Mark L S, 1987 "Eyeheight-scaled information about affordances: A study of sitting and stair climbing" *Journal of Experimental Psychology: Human Perception and Performance* **13** 361 – 370

Massaro D W, 1973 "The perception of rotated shapes: A process analysis of shape constancy" *Perception & Psychophysics* **13** 413 – 422

Matin L, Li W, 1994 "Spatial summation among parallel lines across wide separation (50 deg): spatial localization and the Great Circle Model" *Vision Research* **34** 2577 – 2598

Matin L, Li W, 1995 "Multimodal basis for egocentric spatial localization and orientation" *Journal of Vestibular Research* **5** 499 – 518

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

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

Nakayama K, 1977 "Geometric and physiological aspects of depth perception", in *3D Image Processing* Ed. S Benton (*Society of Photo-Optical Instrumentation Engineers Proceedings* **120** 1 – 8)

Norman J F, Todd J T, Perotti V J, Tittle J S, 1996 "The visual perception of three-dimensional length" *Journal of Experimental Psychology: Human Perception and Performance* **22** 173 – 186

Ooi T L, He Z J, 2004 "Quantitative descriptors of the relationships between physical and perceived distances based on the ground surface representation mechanism" *Journal of Vision* **4**(8) 19a (abstract), http://journalofvision.org/4/8/19/

Ooi T L, He Z J, Wu B, 2002 "Delineating the perceived ground surface from a direction constancy rule" *Journal of Vision* **2**(7) 716a (abstract), http://journalofvision.org/2/7/716/

Ooi T L, Wu B, He Z J, 2001 "Distance determined by the angular declination below the horizon" *Nature* **414** 197 – 200

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

Purdy W C, 1960 "The hypothesis of psychophysical correspondence" General Electric Technical Information No R60ELC56

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, 1983 "Environment centered representation of spatial layout: available information from texture and perspective", in *Human and Machine Vision* Eds A Rosenthal, J Beck (New York: Academic Press) pp 425 – 458

Sedgwick H A, 1986 "Space perception", in *Handbook of Perception and Human Performance* Eds K R Boff, L Kaufman, J P Thomas (New York: John Wiley) pp 21.1 – 21.57

Sinai M J, Ooi T L, He Z J, 1998 "Terrain influences the accurate judgement of distance" *Nature* **395** 497 – 500

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 & Psychophysics* **40** 85 – 92

Tyler C W, 1991 "The horopter and binocular fusion", in *Binocular Vision* Ed. D Regan (Boca Raton, FL: CRC Press) pp 19 – 37

Vishton P M, Rea J G, Cutting J E, Nunez L N, 1999 "Comparing effects of the horizontal – vertical illusion on grip scaling and judgment: relative versus absolute, not perception versus action" *Journal of Experimental Psychology: Human Perception and Performance* **25** 1659 – 1672

Wade N J, 1998 *A Natural History of Vision* (Cambridge, MA: MIT Press)

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

Wallach H, O'Leary A, 1982 "Slope of regard as a distance cue" *Perception & Psychophysics* **31** 145 – 148

Warren W H, Whang S, 1987 "Visual guidance of walking through apertures: Body-scaled information for affordances" *Journal of Experimental Psychology: Human Perception and Performance* **13** 371 – 383

Wraga M, Creem S H, Proffitt D R, 2000 "Perception – action dissociations of a walkable Müller-Lyer configuration" *Psychological Science* **11** 239 – 243
Wu B, He Z J, Ooi T L, 2002 "A ground surface based space perception in the virtual environment" *Journal of Vision* **2**(7) 513a (abstract), http://journalofvision.org/2/7/513/
Wu B, Ooi T L, He Z J, 2000 "Perceived object's location in the dark is not veridical, but not fortuitous" *Investigative Ophthalmology & Visual Science* **41**(4) S228 (abstract)
Wu B, Ooi T L, He Z J, 2004 "Perceiving distance accurately by a directional process of integrating ground information" *Nature* **428** 73 – 77
Wu J, He Z J, Ooi T L, 2002 "Optic flow influences the visually perceived eye level" *Journal of Vision* **2**(7) 512a (abstract), http://journalofvision.org/2/7/512/
Wu J, He Z J, Ooi T L, 2003 "Vertical and horizontal references determined by linear perspective and optic flow information" *Journal of Vision* **3**(9) 499a (abstract), http://journalofvision.org/3/9/499/
Wu J, He Z J, Ooi T L, 2005 "Visually perceived eye level and horizontal midline of the body trunk influenced by optic flow" *Perception* **34** 1045 – 1060

Appendix

The angular declination of the L-shaped target in experiment 2 is the same as the optical slant of the L-shaped target, since the L-shaped target was either placed on the flat floor or parallel to the flat floor. Consequently, one can relate RAR to the optical slant of the L-shaped target. For a generalized relationship that accounts for a possible slant of the physical ground surface with a geographical slant θ, we can write the trigonometric equations as:

$$\mathrm{RAR} = \frac{\sin(\alpha + \theta - \Delta\alpha)}{\sin(\alpha + \theta - \Delta\alpha + \eta)}\,, \tag{A1}$$

$$\mathrm{RAR} = \frac{\sin(O - \Delta\alpha)}{\sin(O - \Delta\alpha + \eta)}\,. \tag{A2}$$

In equation (A2), η is the angular difference (or error) between the perceived and physical geographical slants of the surface, and O is equal to $(\alpha + \theta)$, which is the optical slant of the target.

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