Published in final edited form as:

J Exp Psychol Hum Percept Perform. 2014 April ; 40(2): 626–638. doi:10.1037/a0033034.

The visual system's intrinsic bias influences space perception in the impoverished environment

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Abstract

A dimly lit target in the intermediate distance in the dark is judged at the intersection between the target's projection line from the eye to its physical location and an implicit slanted surface, which is the visual system's *intrinsic bias*. We hypothesize that the intrinsic bias also contributes to perceptual space in the impoverished environment. We first showed that a target viewed against sparse texture elements delineating the horizontal ground surface in the dark is localized along an implicit slanted surface that is less slanted than that of the intrinsic bias, reflecting the weighted integration of the weak texture information and intrinsic bias. We also showed that while the judged egocentric locations are similar between 0.15-5 sec exposure durations, the judged precision improves with duration. Furthermore, the precision for the judged target angular declination does not vary with the physical angular declination and is better than the precision of the eye-to-target distance. Second, we used both action and perceptual tasks to directly reveal the perceived surface slant. Confirming our hypothesis, we found that an L-shaped target on the horizontal ground with sparse texture information is perceived with a slant that is less than that of the intrinsic bias.

Keywords

Distance; Intrinsic bias; Memory; Perceptual space; Slant

A blindfolded observer can walk accurately to a remembered target location on a continuous ground surface in a cue-rich environment, but fails to do so when the ground surface is interrupted by a gap, texture boundary, or an obstacle (e.g., He et al, 2004; Loomis, et al, 1992, 1996; Loomi & Philbeck, 2008; Philbeck, O'Leary, & Lew, 2004; Rieser, Ashmead, Talor, & Youngquist, 1990; Sinai et al, 1998; Thomson, 1983; Wu et al, 2004). These findings support the tenet that the visual system uses an uninterrupted ground surface as a reference frame for space perception beyond the near distance range (>2-3 m) (e.g., Bian & Andersen, 2011; Bian, Braunstein, & Andersen, 2005, 2006; Fera, Braunstein, & Andersen, 2003; Gibson, 1950, 1979; He et al., 2004; Lappin, Shelton, & Rieser, 2006; Meng & Sedgwick, 2001, 2002; Ooi, Wu, & He, 2001, 2006; Ooi & He, 2007; Philbeck & Loomis,

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1997; Sedgwick, 1986; Sinai, et al., 1998; Sugar, McBeath, Wang, 2006; B. Wu, He, & Ooi, 2004, 2007a&b; J. Wu, He, & Ooi, 2005, 2008). Adoption of the ground surface strategy for space perception is likely associated with several factors (Gibson, 1950, 1979; He & Ooi, 2000; Sedgwick, 1986). First, we normally stand, navigate and interact with both animate and inanimate objects on the ground surface. Second, the ground carries rich and reliable depth information (e.g., texture gradients) that often extends from our feet to the far distance. Third, by coding 3-D object locations with reference to the common 2-D ground surface, the visual system can improve its coding efficiency (by reducing one dimension).

We proposed a Sequential Surface Integration Process (SSIP) hypothesis to elaborate on how the visual system constructs the ground surface representation as a reference frame for space perception in the intermediate distance range (He et al, 2004; Wu et al, 2004). It posits that in the normal full cue viewing condition, the SSIP begins by representing the near ground surface region using the accurately coded near depth information, such as absolute motion parallax, binocular disparity, etc. This leads to a locally accurate near ground representation, which the visual system capitalizes on as an anchoring surface to sequentially integrate with the farther ground regions that predominantly carry texture gradient information. The outcome of the SSIP is a global surface representation of the ground expanse that is used as the reference frame for space perception.

However, when the visual system cannot access the depth information on the ground, the visual system employs the *intrinsic bias* as its reference frame (Gogel & Tietz, 1973; Ooi et al, 2001, 2006). The intrinsic bias is revealed in the dark environment where the ground cannot be seen and other depth information is absent. In this situation, a dimly lit target on the horizontal ground is perceived at the intersection between its projection line from the eye and an implicit slanted surface, rather than at its physical location or any other random locations (figure 1a). We have proposed that the implicit surface reflects the intrinsic bias, which represents the visual system's internal model of the ground surface (Ooi et al, 2001, 2006). Further supporting the hypothesis, it has been shown that the intrinsic bias determines the perceived shape and size of a dimly lit plane target in the dark (Aznar-Casanova et al, 2011; Ooi et al, 2006; Zhou et al, 2010, *in press*). For example, as illustrated in figure 1b, we found that the slant derived from the perceived aspect ratio (width/length in depth) of a horizontal L-shaped target in the dark is similar to that of the intrinsic bias (Ooi et al, 2006). In other words, it is as if the L-shaped target is perceived as resting on the intrinsic bias (implicit surface) in perceptual space.

The intrinsic bias possibly originates from one's past experience with the statistical properties of the natural scenes, where humans, animate and inanimate objects are either directly, or indirectly, supported by the ground (Yang & Purves, 2003). Consequently, when the ground is not visible, the visual system capitalizes on the intrinsic bias to make an “educated” guess of the target's location. Extending this idea, we hypothesize that the visual system also capitalizes on the intrinsic bias for space perception when the depth information on the horizontal ground is weak and/or ambiguous, i.e., in a reduced cue condition (impoverished environment). Thus, in addition to the SSIP that integrates the weak texture gradient (depth) cue, the intrinsic bias influences the process of ground surface representation. The outcome is a slanted surface representation of the horizontal ground whose slope is less steep than that of the intrinsic bias (figure 1c).

Figure 2a (left) shows a reduced cue condition in the dark where the horizontal ground surface is sparsely delineated by a 2×3 array of texture elements to provide a weak texture gradient depth information. Our hypothesis predicts that the global ground surface representation will be slanted upward, resulting in the target on the floor being perceived above the floor at the intersection of the eye-to-target projection line and the slanted ground

representation (figure 2a, right). This prediction opposes an alternative hypothesis that the intrinsic bias only contributes to space perception in the dark but not when there exists texture gradient information on the ground. Ooi & He (2007) argued that such an alternative “horizontal compression hypothesis” would predict that the ground surface representation is horizontally compressed (figure 2c). In other words, the alternative hypothesis predicts that the perceived angular declination is increased ($\alpha' > \alpha$, figure 2c) rather than remains unchanged ($\alpha' \leq \alpha$, figure 2a and 2b). Clearly, one approach to verifying between these competing hypotheses is to empirically obtain the perceived surface slant and the angular declination of the target on the ground.

We thus conducted two experiments using discrete (figure 2a) and plane (figure 2b) targets with perceptual- and action-based tasks in the dark and reduced cue conditions. Our first experiment measured the observer's judged egocentric locations of discrete targets using the blind walking-gesturing task (Ooi et al, 2001). The profile of the judged target locations from this task reveals the shape of ground surface representation and the perceived angular declination. Complementing this, our second experiment reveals the slant of the ground surface representation by measuring judged exocentric distance of an L-shaped target placed horizontally on the ground (figure 2b). We used a perceptual task based on aspect ratio judgment (Loomis et al, 2002; Loomis & Philbeck, 1999; Ooi et al, 2006; Wu et al, 2004; Wu J et al, 2008) and visually directed tasks using the palm board (He et al, 2007; Proffitt et al, 1995; Witt & Proffitt, 2007) and blind walking tasks (Creem-Regehr et al, 2005; Loomis et al 1992, 1996; Ooi et al, 2001; Philbeck et al, 2004, 2008; Rieser et al, 1990; Sinai et al, 1998; Thompson, Dilda, & Creem-Regehr, 2007; Thomson 1983; Wraga, Creem, & Proffitt, 2000).

Experiment 1. Perceptual space revealed by judged egocentric locations

We used the blind walking-gesturing task to measure the judged location of a dimly lit target in three conditions: dark, parallel-texture and convergent-texture (figure 3). The latter two conditions had sparse texture elements on the horizontal ground in the dark room, constituting two types of reduced cue conditions. We predicted that the target location would be judged as if they were placed on a slanted surface.

We also examined the temporal dynamics of surface representation in all three conditions by varying the stimulus presentation duration. We have found that the integration of texture information into a global surface representation takes time (Su et al, 2011). Presumably, with a stimulus duration shorter than the putative critical integration period in the reduced cue condition, the SSIP might not be able to adequately integrate the texture gradient information on the ground. Consequently, the ground surface representation might be more reliant on the intrinsic bias. Related to this issue of integration, Philbeck and his colleagues discovered that their observers were able to extract angular size and angular declination information for distance perception at very short exposure durations in the full cue condition (Gajewski et al, 2010; Philbeck, 2000). It would be interesting to reveal whether the visual system can also be as efficient in the reduced cue conditions.

Method

Observers—Nine observers with informed consent and who were naïve to the purpose of the study participated in the experiment. All observers had self-reported normal or corrected-to-normal vision. Throughout the experiment, the observers viewed the stimulus setup with the motor dominant eye and had the fellow eye patched. Even though the effect of monocular texture gradient cue can still be revealed in the presence of binocular disparity cue (Wu et al, 2007b), we decided to avoid the potential confound of the binocular disparity cue since one of our goals was to compare the difference between the two types of texture

gradient patterns (parallel vs. convergent). We used binocular viewing in Experiment 2 because this was no longer a concern since we only tested with parallel texture pattern.

Stimulus configuration and environment—Observers were tested in a completely dark room (3×11 m) with a dimly lit test target and textured background, except in the dark condition. The stimulus presentations were controlled by a computer. The test target was an internally illuminated red ping-pong ball (~ 0.16 cd/m²) that was encased in a box. An adjustable aperture in the front of the box set the visual angle of the target at 0.27 deg when measured at the eye level. The test target was placed at one of six possible locations, comprising of combinations of two heights (on the floor and 0.5m above the floor) and three horizontal distances from the observer (3.75, 5.00, and 6.25 m). Figure 3a provides a side view of the parallel-texture condition. Figures 3b and 3c, respectively, illustrate the top view of the 2×3 array of the parallel-texture and convergent-texture background conditions tested. Each texture element was made of an internally illuminated white ping-pong ball (0.20 cd/m²) housed inside a small box with a fixed circular aperture of 6 cm in diameter. All texture elements were placed on the floor for the test trials, and about 0.3 m above the floor for the catch trials. The catch trials accounted for one sixth of the total number of trials. The purpose of having the catch trials was to prevent the observers from assuming that the height of the texture background was constant.

A lighted fixation target, with the same dimensions as the texture elements, was used to control the observer's eye fixation position prior to the onset of the test display. It was always placed on the floor and its angular declination was halfway between the test target position with the largest angular declination and the test target position with the smallest angular declination among all six-target locations. The angular declination difference between these two extreme positions was about 14° for our observers.

Display sequence—During a trial, the computer first turned on the fixation target for 1.5 s. Then after a 1.5 s waiting period in complete darkness, the computer turned on the test display for one of three predetermined stimulus durations (0.15, 0.5, or 5.0 s). This ended the trial and the observer made the appropriate responses.

Design—The current experiment used a fully crossed factor design with three factors, which are stimulus durations (0.15, 0.5 and 5.0 s), texture background conditions (dark, parallel-texture, and convergent-texture) and target locations (6 combinations of three horizontal distances and two heights). Each condition was tested twice. Within an experimental session, the test trials (texture background on the floor) and catch trials (texture background 0.3m above the floor) were tested in a random order. Only the data obtained from the test trials were analyzed.

Procedure—A test trial began with the observer stepping onto two small fluorescent dots on the floor for correct positioning in the dark. When he/she indicated readiness for the trial, the experimenter activated the computer to turn on the fixation point and to simultaneously beep for 0.5 sec to alert the observer of the fixation point onset. After the fixation light (1.5 sec) was turned off, the observer maintained his/her fixation posture in the dark for another 1.5 sec. Then, the test display was presented. The observer was instructed to judge the target location without making head and body movements, although eye movements were allowed. At the end of the test display presentation, the observer closed his/her eyes and told the experimenter when he/she was ready to walk. Whereupon the experimenter quickly and quietly cleared out the walking path in front of the observer and instructed the observer to begin the blind-walking-gesturing task. The observer walked blindly to the (remembered) judged target location with his/her right hand sliding along a guidance rope for safety. (The

rope was tied across the length of the room at a height of 1 m above the floor.) Upon reaching his/her destination, the observers gestured the height of the judged target with the left hand. The experimenter recorded the walked distance and gestured height, and then instructed the observer to walk back to the observation location and wait for the next trial. The observer received no feedback regarding his/her performance. Music was played aloud during the trial to mask the possible acoustic clues to distance.

Results and Discussion

(a) Accuracy of judged target locations—Figure 4 depicts the average results of the three background conditions [i.e., dark (no background), parallel-texture and convergent texture conditions]. The open cross symbol represents the physical target location. The open triangle, gray square and black circular symbols depict the judged target locations, respectively, for the 0.15, 0.5, and 5.0 sec stimulus durations. Each oblique dash line that links the average eye position on the y-axis to the physical target represents the physical eye-to-target projection line. The graphs in the left and right panels depict the results for the targets on the floor and 0.5m above the floor, respectively.

Effect of stimulus duration: The judged target locations with the three durations cluster together for all the three background conditions, indicating a lack of systematic influence of stimulus duration on judged target location. This is confirmed by a 4-way ANOVA with repeated measures (duration $\times$ background $\times$ horizontal distance $\times$ height). Specifically, for the walked distance, the main effect of duration [$F(2, 16)=1.183, p=0.332$] and the interaction effect between duration and background [$F(4, 32)=0.978, p=0.433$] fail to reach the significance level. Similarly, for the gestured height, the main effect of duration [$F(2,16)=1.264, p=0.309$] and the interaction effect between duration and background [$F(4, 32)=1.587, p=0.202$] also fail to reach the significance level. The fact that the observers' performance with the shortest stimulus duration (0.15s) is similar to that with the longest duration (5.0s) suggests that the representation of the ground surface is quite efficient whether in the dark or reduced cue conditions. This finding complements those in the full cue condition (Gajewski et al, 2010; Philbeck, 2000).

Effect of texture background: To better describe the effect of texture background, we averaged the judged locations of the three different durations (since they are similar) from the three background conditions, and plotted the data in figures 5a (target 0.5m above the floor) and 5b (target on the floor). Notably, the data points in both figures are segregated into two groups, i.e., dark (no texture background) vs. the two texture (convergent and parallel) background conditions. For the purpose of analysis below, we consider the two texture conditions under the larger umbrella of “reduced cue conditions”.

We have suggested that the profile of the judged target locations reveals the slant of the ground surface representation. We added regression lines to the data to obtain the slopes for the dark and the reduced cue conditions, in order to estimate the slants of the represented surfaces. For the targets 0.5m above the ground (figure 5a), the slants are 17.6° in the dark and 13.6° in the reduced cue conditions. For the targets on the floor (figure 5b), the slants are 14.3° in the dark and 5.8° in the reduced cue conditions. Clearly, the slants are steeper in the dark (representing the intrinsic bias) than the in the reduced cue conditions. And of significance, the slants in the reduced cue conditions are steeper than the physical slants of the texture elements (zero slant). This indicates that in the reduced cue conditions, the representation of the texture surface is not veridical, but has a surface slant that is partly contributed by the intrinsic bias.

Effect of linear perspective cue: We now consider the difference between the two texture conditions under the “reduced cue” umbrella. Although the judged locations in the parallel-texture and convergent-texture conditions adhere to a single slant profile (figure 5), the targets in the convergent-texture condition are perceived as farther. A careful examination of figure 5 also reveals that the judged targets in the convergent-texture condition have smaller angular declinations. This trend is best illustrated in figure 6, which plots the perceived angular declination as a function of the physical angular declination. The regression functions for the dark and parallel-texture conditions are similar, whereas the regression function for the convergent-texture condition is lower in the graph. This is confirmed by a 2-way ANOVA with repeated measures with the Greenhouse-Geisser correction. Both the main effect of texture [$F(1.172, 9.375)=13.519, p=0.004$] and main effect of target location [$F(1.747, 13.980)=300.725, p<0.001$] are significant whereas the interaction effect fails to reach significance [$F(4.372, 34.978)=1.743, p=0.158$]. Subsequent contrast analysis reveals similarity between the dark and parallel-texture conditions [$F(1, 3)=0.091, p=0.770$], but a significant difference between the dark and convergent-texture conditions [$F(1, 3)=15.276, p=0.004$].

The finding of a reduction in the judged angular declination in the convergent-texture condition is consistent with our previous study showing that the perceived eye level is lower in the convergent-texture condition than in the parallel-texture condition (Wu et al, 2007). Such findings serve as a reminder of the trigonometric relationship dictating space perception (Ooi & He, 2007). Namely, besides the ground surface representation, changes in the perceived eye level can affect perceived angular declination, and therefore, judged distance [Ooi et al, 2001 (adaptation to prism); Wu et al, 2005 (adaptation to optic flow)].

The current finding of a difference between the two texture background conditions also supports our previous study that used the verbal report and blind throwing tasks to investigate how linear perspective and texture compression on the ground surface affect space perception (Wu et al, 2007b). That study revealed the reported egocentric distance in the convergent-texture condition was farther than in the parallel-texture condition, and that the judged eye level was lower in the convergent-texture condition. Our current study further shows that using texture elements to manipulate linear perspective information mainly affects the overall angular declination and less the orientation (slant) of the ground surface representation.

(b) Precision of judged target locations—We next quantified the precision of performance based on the inter-trial variability (standard deviation) in the judged target locations in polar coordinates (eye-to-target distance and angular declination). This is plotted as the two orthogonal error bars in figure 5, which represent the inter-trial variabilities at each judged target location. The error bar parallel to the eye-to-target projection line direction represents the inter-trial variability of the eye-to-target distance. Meanwhile the orthogonal error bar represents the inter-trial variability of angular declination scaled to the judged eye-to-target distance (i.e., the inter-trial variability of angular declination $\times$ average judged eye-to-target distance of the target). Two notable trends are immediately clear from these graphs. First, the inter-trial variability in the eye-to-target distance changes with target location, as confirmed by ANOVA [main effect of the target location $F(5, 40)=8.837, p<0.001$]. For example, for the dark condition in either figure 5a or 5b, there is a clear trend where the error bars representing the inter-trial variability of the eye-to-target distance becomes longer with increasing physical target distance. This indicates that the precision of the judged eye-to-target distance for a target at near distance is better than for a target at far distance. Second, in all three graphs, the scaled inter-trial variability of angular declination is smaller than that of the eye-to-target distance inter-trial variability. A similar trend has been found in full cue conditions (Ooi & He, 2007). For

further analyses, below we performed a 3-way ANOVA with repeated measures to reveal the impacts of texture backgrounds, target locations, and stimulus durations on the inter-trial variability in angular declination (figure 7a & 7c) and in eye-to-target distance (figure 7b & 7d).

For the inter-trial variability in angular declination, the main effects of stimulus duration [$F(2, 16)=12.130, p<0.001$] and texture background [$F(2, 16)=5.150, p=0.019$] are significant, while the main effect of target location (angular declination) and other interaction effects fail to reach the significance level ($p>0.05$). To better illustrate the main effects of stimulus duration and texture background, we plot in figure 7a, the inter-trial variability in angular declination as a function of the stimulus duration. (Note that each data point in figure 7a represents the average of the 6 test target locations since the main effect of target location is not significant.) The inter-trial variability in angular declination decreases with stimulus duration, suggesting that observers judge the angular declination more precisely at longer stimulus durations. Figure 7a also shows that the inter-trial variability in angular declination is larger in the dark than in the other two texture conditions [dark vs. convergent-texture: $F(1, 8)=5.863, p=0.042$; dark vs. parallel-texture: $F(1, 8)=5.269, p=0.051$; 2-way ANOVA with repeated measures]. This indicates that the observers' judge angular declination with better precision when there exists texture information on the ground than when it is not visible in the dark.

Figure 7c plots the inter-trial variability in angular declination as a function of physical target angular declination (each data point represents the average of the three background conditions). Clearly, the precision does not increase significantly with the physical target's angular declination ($p>0.05$). This indicates that the precision in judged angular declination for a target at near distance (large angular declination) is about equivalent to the precision for a target at far distance (smaller angular declination). This remarkable precision for angular declination differs from the precision for the eye-to-target distance (below). Thus, along with the finding of a veridical perception of angular declination, this reveals that the visual system accurately and precisely represents the angular declination (direction) information, which is a critical factor for constructing perceptual space (Ooi et al, 2001, 2006; Wu et al, 2005).

We performed a similar analysis for the inter-trial variability in the eye-to-target distance. We found that the main effects of stimulus duration [$F(2, 16)=2.425, p=0.120$], texture background [$F(2, 16)=2.346, p=0.128$] and all other interaction effects fail to reach the significance level ($p>0.05$). Figure 7b plots the inter-trial variability in eye-to-target distance as a function of stimulus duration, where each data point represents the average of 6 test target locations. Although the inter-trial variability in the eye-to-target distance appears to decrease with increasing stimulus duration, the statistical analysis fails to reach the significance level ($p>0.05$). Figure 7d plots the ratio of the inter-trial variability of judged eye-to-target distance to the judged eye-to-target distance (similar to Weber's fraction) as a function of the physical eye-to-target distance. Clearly, the ratios are largely constant for all physical eye-to-target distances. Indeed, all the calculated slopes of the regression lines are close to zero [5s duration: slope= $2.39\text{E-}05, r^2=0.011$; 0.5s duration: slope= $-2.19\text{E-}05, r^2=0.0078$; 0.15s duration: slope= $1.105\text{E-}06, r^2=0.0085$].

Experiment 2: Perceptual space revealed by judged exocentric distance

Experiment 1 above revealed that in the reduced cue conditions with sparse texture elements delineating the horizontal ground, egocentric target locations are judged as nearer and above the ground as if they are seen to be reclining on an implicit slanted surface (figure 4). The finding supports our hypothesis that the ground surface representation is slanted due to the

contribution of the intrinsic bias when the depth information is inadequate (figure 2a). Complementing this, the current experiment used a planar L-shaped target and asked observers to directly, and indirectly, report the perceived slant of the target. Since the L-shaped target was placed on the horizontal ground, its perceived slant should reflect the orientation of the ground surface representation (figure 2b).

We used three different tasks to measure the observer's perception in two conditions: dark (figure 8a) and parallel-texture (figure 8b) conditions. In one perceptual-based task, the observer judged the aspect ratio (the width/length in depth) of the L-shaped target, from which we derived the perceived surface slant (Ooi et al, 2006). Then in two different action-based tasks (palm board and blind walking), we asked the observer to orient his/her palm to directly indicate the perceived slant of the L-shaped target.

Method

Observers—Eight observers with informed consent who were naïve to the purpose of the study participated in the experiment. Two of the observers also participated in Experiment 1. They all had self-reported normal vision and clinically normal stereo acuity (<40 arc sec with the StereoFly test). Throughout the experiment, the observers were tested with binocular viewing.

Stimulus configuration and environment—The experiment was conducted in an 8×10 meter dark room. A small area at the end of the room, separated by a black curtain, served as the waiting area for the observer during the experiment. The observer wore a wireless headphone with music played aloud to mask potential auditory cues during the experiment.

The L-shaped target was constructed with two florescent strips that were taped to two wooden bars that formed an L pattern. The limb oriented in depth (length, L) had a fixed length (standard), while the other limb oriented in the frontoparallel plane (width, W) was variable and could be adjusted by the experimenter. At each test location, the dimension of the L-shaped target was chosen as specified in the table below. It was determined so that the visual angle of the length (in depth) of L-shaped target at each location was roughly 3.3° on the assumption that the observer's eye height was 160 cm, which was close to the average observers' eye height. The dimensions in the first two columns of the table were used for the test trials while those in the last four columns were used for the catch trials. The widths of the florescent strips had a similar visual angle, i.e., 1 inch at 6 m and 0.75 inch at 4 m.

Location (distance, height)	4m, 0m	6m, 0m	3m, 0.5m	4m, 0.5m	5m, 0.5m	6m, 0.5m
Length (L)	25cm	55cm	20cm	35cm	55cm	80cm

The parallel-texture background consisted of a 2×4 array of eight florescent stars (3 cm in diameter and ~ 0.3 cd/m²). We used a 2×4 array here instead of a 2×3 array as in Experiment 1 to further maximize the coverage of the texture pattern. This ensured that the perceived slant of the L-shaped target, whose size was substantial, was largely affected by the texture background. The eight florescent stars were placed at distances 2, 3.5, 5 and 6.5 m apart, arranged in two parallel columns separated by 1.5 m (figure 8b).

The palm board used in the palm orientation task was a 30×25 cm metal plate, set at a height of about 1.2 m and placed directly in front of the observer when he/she was standing at the observation position. The palm board could be rotated in a seesaw-like fashion in a full circle, around a horizontal axis parallel to the observer.

Design—The three factors in the experiment were combinations of target distance (4 m and 6 m, both on the floor), stimulus condition (dark and parallel-texture), and task (aspect ratio, palm-board, walking and palm-orienting). Each observer was tested with two trials for a given combination. Five catch trials were inserted during the experiment. The order of trial presentation was randomized.

Procedure—To begin an experiment, the experimenter led the observer in blindfold to the waiting area of the test room. The experimenter then placed the L-shaped target at the test location. The initial width of the L-shaped target was approximately 0.5 or 0.8 times its length. The choice between these two values was counterbalanced between trials.

After the target setup, the observer walked from the waiting area to the testing area and stepped on two florescent elements on the floor for correct positioning. For each trial, the observer performed three consecutive tasks, i.e., palm board/palm orientation, aspect ratio, and walking/palm-orientation tasks.

First, the observer responded to the perceived geographical slant of the L-shaped target using the palm board/palm orientation task. He/she placed his/her motor-dominant hand on the board and rotated the board without looking at it, until he/she judged the board orientation to be the same as that of the L-shaped target. Once the observer completed the task, the experimenter measured the palm board's geographical slant using a digital inclinometer (Smart Tool Sensor Module) and removed the palm board.

In the second consecutive task of the same trial, the observer performed the aspect ratio task. He/she was instructed to use the criterion of perceived dimension to match the length and width of the two limbs of the L-shaped target (Loomis & Philbeck, 1997; Ooi et al, 2006; Wu et al, 2008). The observer stood at the observation position and verbally told the experimenter to either reduce or extend the width of the L-shaped target by some fraction of its width. The adjustment was typically performed several times until the observer was satisfied with his/her aspect ratio judgment. The final adjusted physical width was taken as the matched width. The ratio of the matched width to the physical length in depth is the actual physical aspect ratio of the matched L-shaped target.

In the third consecutive task of the same trial, the observer walked blindly to traverse the perceived distance of the L-shaped target. Upon reaching the remembered destination, he/she put his/her motor-dominant hand at the previously perceived vertex of the L-shaped target and slanted his/her palm to the remembered slope. The criterion was as if he/she was spreading his/her palm over the perceived surface of the L-shaped target. The observer was encouraged to integrate the three responses into one natural task: encoding the target, walking to its perceived location, and placing his/her hand along its (perceived) surface at the vertex. The experimenter then used the digital inclinometer to measure the geographical slant of the observer's palm.

Results and Discussion

(a) Actual physical aspect ratio of the matched L-shaped target on the ground and the derived surface slant—Figure 9 shows the mean actual physical aspect ratios (width/length in depth) of the matched L-shaped target on the ground in the dark condition (circles) and in the parallel-texture condition (squares). The actual physical aspect ratios are smaller than unity and decrease with the physical target distance, indicating that foreshortening increases with target distance [$F(1,7)=55.399$, $p<0.001$, 2-way ANOVA with repeated measures]. Moreover, the actual physical aspect ratios are significantly larger in the parallel-texture than in the dark condition [main effect of stimulus condition: $F(1,7)=54.330$,

$p < 0.001$; interaction effect between stimulus condition and target distance: $F(1,7)=2.002$, $p=0.2$].

We then converted the actual physical aspect ratios to perceived slants following the method used in Ooi et al (2006). These are depicted in figure 10a. As predicted, there exist noticeable surface slants in both the dark and parallel-texture conditions, with the former having a larger surface slant than the latter.

(b) Judged surface slant of the L-shaped target on the ground with visually directed action tasks—Figures 10b & 10c depict the mean judged surface slants of the L-shaped target on the ground measured with the palm board/palm-orientation and the walking/palm-orientation tasks, respectively. The figures clearly reveal that the L-shaped target on the horizontal ground surface was judged as slanted in both conditions. Furthermore, perceiving the L-shaped target as slanted in the parallel-texture condition supports the hypothesis that the intrinsic bias contributes to ground surface representation in the reduced cue condition (figure 2b). We also found that the judged surface slant is smaller in the parallel-texture than in the dark condition [palm board/palm-orientation: $F(1,7)=51.189$, $p < 0.001$; walking/palm-orientation: $F(1,7)=38.287$, $p < 0.001$, 2-way ANOVA with repeated measures]. This confirms the proposal that the ground surface representation in the reduced cue condition is obtained from the integration of the external depth cues and intrinsic bias. Additionally, for both conditions, the judged slants increase with the distance of the L-shaped target [palm board/palm-orientation: $F(1,7)=37.233$, $p < 0.001$; walking/palm-orientation: $F(1,7)=8.636$, $p < 0.025$]. But the difference (in the distance factor) between the dark and parallel texture conditions at 4m or 6m is about the same [palm board/palm-orientation: $F(1,7)=1.265$, $p=0.298$; walking/palm-orientation: $F(1,7)=0.573$, $p=0.474$].

Comparing the three graphs in figure 10, we found the derived surface slants with the palm-board task to be smaller than those with the other two tasks [palm board/palm-orientation vs. aspect ratio: $F(1,7)=13.573$, $p < 0.01$; palm board/palm-orientation vs. walking/palm-orientation: $F(1,7)=4.826$, $p=0.064$]. However, the surface slants derived from the aspect ratio and walking/palm-orientation tasks are similar [$F(1,7)=0.422$, $p=0.537$]. One possible explanation for the measured slant with the palm board/palm-orientation task being smaller is because the palm board was set at a height of about 1.2 m above the ground. We previously found that when the arm is extended downward, there is a mechanical constraint on the wrist that can reduce the gestured palm orientation (He et al, 2007). This mechanical constraint was also observed by Durgin et al (2010).

In addition, we found in the dark condition, that the derived slant with the aspect ratio task (figure 10a) is about 12° - 14° , which is in the same range as that in Experiment 1 with the blind walking-gesturing task ($\sim 14.3^\circ$, figure 5b). These slant magnitudes are also close to the ones reported from our previous studies (blind walking-gesturing task: 12.4° ; aspect ratio task: 14.4° , Ooi et al 2006). As for the reduced condition (parallel-texture), the derived slant with the aspect ratio task (square symbols, figure 10a) is about 8° - 11° , which is slightly higher than that obtained in Experiment 1 (5.8°) with texture elements on the floor.

Overall, the results from the three different tasks (figure 10) exhibit a similar trend, wherein the L-shaped target is perceived as slanted in both the dark and parallel-texture conditions. The perceived slant increases with distance and is larger in the dark condition. The increase in the perceived surface slant of the L-shaped target with target distance (or decreases with the angular declination of the target) creates a slant profile similar to the shape of the intrinsic bias, whose surface slant becomes larger at the far distance (figure 1). These

findings confirm the hypothesis that the intrinsic bias contributes to the ground surface representation in the reduced cue condition.

General Discussion

We tested the hypothesis that the intrinsic bias makes a significant contribution to the ground surface representation when the depth information is inadequate in the reduced cue condition (figures 2a & 2b). Confirming it, our first experiment revealed that dimly lit targets were not perceived on the horizontal ground surface that was sparsely delineated by texture gradient information but were perceived as if reclining on an implicit slanted surface above the ground. Yet, despite the misperceived locations, the perceived angular declinations of the targets did not increase. These findings can be taken as direct evidence against the alternative “horizontal compression” hypothesis that distance is underestimated due to the ground surface representation compressing horizontally and the perceived angular declination increasing (figure 2c). Our current study is well positioned to address the “horizontal compression” hypothesis because we measured the judged target location, i.e., the distance *and* height of the perceived target. In contrast, most previous space perception studies only measured target distance, and thus could not directly test the “horizontal compression” hypothesis. As mentioned, the ground surface representation acts as a reference frame for space perception (Gibson, 1950, 1979; Sedgwick, 1986; He et al, 2000; Ooi & He, 2007). Therefore, an important theoretical implication of revealing the slanted ground surface representation in the reduced cue conditions is that it informs how perceptual space in the intermediate distance range is shaped when the depth information is insufficient. Further, complementing Experiment 1, our second experiment that used three different tasks to measure surface orientation found that a horizontal L-shaped target on the ground surface with sparse texture gradient information was perceived as slanted toward the frontoparallel plane.

Additionally, by analyzing the precision of performance in the dark and reduced cue conditions, we revealed that the precision of judged angular declination is superior to that of the eye-to-target distance. In fact, the former did not vary with the physical angular declination, whereas the latter deteriorates as the physical eye-to-target distance increased, in a manner that follows Weber's law (figures 5 & 7). This is because distance is scaled from its origin at the observation point. Conversely, this suggests that the coding of the angular declination (direction) is independent of the viewing distance.

The current study is the first to obtain a profile of the ground surface representation in the reduced conditions and to demonstrate the influence of the intrinsic bias. The finding augments previous indirect evidence showing that the intrinsic bias influences the ground surface representation when the ground surface is interrupted due to an abrupt change in the texture gradient information on the ground surface (Feria et al, 2003; He et al, 2004; Sinai et al, 2008; Wu et al, 2007a). For example, Wu et al (2007a) tested observers' space perception of a virtual environment scene created in a Head Mounted Display (HMD). They found that relative to a target on a homogeneous texture ground surface, distance was underestimated when the target was located on a ground location beyond a texture boundary. Additionally, the ground surface beyond the texture boundary was not perceived as coplanar with the near ground surface (where the observers stood), but was perceived as slanted upward. This indicates that the intrinsic bias contributes to ground surface representation when the SSIP fails to accurately integrate the texture gradient information (He et al, 2004; Wu et al, 2004).

Finally, we also attempted to reveal the time course of surface representation as the SSIP integrates the sparse texture information in Experiment 1. However, we did not find a reliable effect of stimulus duration on perceived target location. For example, the accuracy

of the judged target location with 0.15 sec exposure was the same as that with 5 sec exposure. This result has a parallel with the study by Philbeck (2000). He found that as little as 0.15 sec of target/surface layout viewing duration was sufficient for accurate egocentric distance judgment of a target on the horizontal ground surface using the blindfolded walking task. One important implication of Philbeck's study, and ours, is that the ground surface integration process occurs quite rapidly. It ably forms a large ground surface representation without requiring integration across gaze shifts.

An important question is what facilitates the ground surface representation of the texture information? One possibility is related to the ability of the visual system to continue the surface integration process even after the physical stimulus (surface layout) is removed. This is because no mask was used in Philbeck's study, thus permitting the visual system to continue the integration based on visual persistence. The same reasoning applies to our experiment. However, a recent work by Gajewski et al (2010) reveals that even with a mask, observers can extract angular size and angular declination information for distance perception of a target on the ground at a short stimulus duration. Another possible reason for the facilitated surface integration process is that the observers could have a prior knowledge of the ground surface being horizontal and having the same height as the floor they stood on. But this is unlikely in our experiment. This is because our observers did not know that the tested texture background was always placed on the ground as we inserted catch trials where the texture background was raised about 30 cm above the floor. These being said, while we do not yet know what facilitates the ground surface representation of the texture information, we are pleasantly surprised by its efficiency (Su et al, 2011). On the other hand, its efficiency is befitting of a system that serves as a reference frame for space perception, namely, the ground surface representation.

Acknowledgments

This research was supported by the National Institutes of Health Grant R01-EY014821 to Zijiang J. He and Teng Leng Ooi.

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Figure 1.

Space perception based on the visual system's intrinsic bias and external depth information. (a) A dimly lit target in an otherwise dark environment is perceived at the intersection between its projection line and the visual system's intrinsic bias (slanted curve). (b) A dimly lit L-shaped target in the dark is perceived as slanted along the intrinsic bias. (c) The sequential surface integration process (SSIP) constructs the ground surface representation by integrating the texture information on the ground. It is predicted that when the texture information is insufficient (reduced cue condition), the ground surface representation will be a slanted surface due to the influence of the intrinsic bias.

Figure 2.

Predictions of space perception in a reduced cue condition where a 2×3 array of dimly lit texture elements delineates the horizontal ground in the dark. (a) The SSIP hypothesis predicts the ground surface representation that acts as a reference frame for space perception is slanted. Thus a dimly lit target is perceived as if located on the slanted surface. (b) Similarly, the SSIP hypothesis predicts a horizontal L-shaped target being perceived as slanted. (c) Opposing the SSIP hypothesis, a horizontal compression hypothesis predicts that the ground surface representation is horizontally compressed toward the observer. One consequence is that the subjective angular declination is larger than the physical angular declination ($\alpha' > \alpha$)

Experiment 1

Figure 3.

Illustration of the stimuli used in Experiment 1. (a) Side view of an observer viewing a target against a parallel-texture background. (b) and (c) Top view of the parallel-texture and convergent-texture background conditions, respectively.

Figure 4.

The average perceived target locations in Experiment 1 in (a) the dark, (b) parallel-texture, and (c) convergent-texture conditions. Note that in all three conditions, the perceived locations of the dimly lit targets with the three different stimulus durations largely cluster together even as they are deviated from the physical target locations.

Figure 5.

The average perceived target locations in Experiment 1. Each symbol represents the average of three perceived locations with different stimulus durations. (a) Targets were located 0.5m above the horizontal ground. (b) Targets were located on the horizontal ground. The average eye position is depicted on the top of the y-axis. It is linked to the physical target locations by the dash projection lines. The error bars are plotted in polar coordinates with the ones pointing to the average eye position being the mean standard errors of the perceived eye-to-target distance, whereas the orthogonal error bars represent the standard errors of angular declination scaled according to the perceived eye-to-target distance. See text for details.

Effect of linear perspective

- Dark: $y = 1.08x - 0.56$
- Parallel-texture: $y = 1.00x + 0.57$
- △ Convergent-texture: $y = 0.99x + 1.38$

Figure 6.

The average judged angular declinations for all the six target locations in the three background conditions. All have slopes close to unity, although the data for the convergent-texture condition are systematically shifted downward.

Precision of performance

Figure 7.

The precisions of performance in Experiment 1 based on inter-trial variabilities (standard deviations). (a) Standard deviation of judged angular declination as a function of stimulus exposure duration. (b) Standard deviation of eye-to-target distance as a function of stimulus exposure duration. In both (a) and (b), each data point represents the average of six target locations. (c) Standard deviation of judged angular declination as a function of the physical target angular declination. (d) Ratio of the standard deviation of the judged eye-to-target distance to the judged eye-to-target distance as a function of the physical eye-to-target distance. In both (c) and (d), each symbol depicts the average of each target location for the three test conditions. See text for details.

Experiment 2

Figure 8.

Illustration of the two stimulus conditions used in Experiment 2. (a) Viewing the L-shaped target in the dark. (b) Viewing the L-shaped target in the presence of a parallel-texture background in the dark.

L-shaped target on the ground

Figure 9.

Actual physical aspect ratios of the matched L-shaped targets in the dark and parallel-texture conditions.

L-shaped target on the ground

Figure 10.

Comparison of the derived surface slant based on three different tasks: (a) the aspect ratio; (b) palm-board/palm orientation; and (c) walking/palm-orientation.