The ground dominance effect in the perception of relative distance in 3-D scenes is mainly due to characteristics of the ground surface

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Previously, we (Bian, Braunstein, & Andersen, 2005) reported a dominance effect of the ground plane over other environmental surfaces in determining the perceived relative distance of objects in 3-D scenes. In the present study, we conducted three experiments to investigate whether this ground dominance is due to inherent differences between ground and ceiling surfaces, or to the locations of these surfaces in the visual field. In Experiment 1, two vertical posts were positioned between a ground surface and a ceiling surface, and optical contact was manipulated so that the two surfaces provided contradictory information about the relative distances of the posts from the participant. The two surfaces were either both above, both below, or one above and one below fixation. In Experiment 2, only one surface was presented, either above, below, or at fixation. In Experiment 3, the posts were replaced by two red dots, and the eccentricity of the optical contact on the two surfaces was equated in each of five locations in the visual field. In all three experiments, participants judged which of the two objects appeared to be closer. Overall, we found a higher proportion of judgments consistent with a ground surface than with a ceiling surface in all locations, indicating that the ground dominance effect is mainly due to characteristics of the ground surface, with location in the visual field having only a minor effect.

The importance of the ground surface in determining perceived relative distance of objects in 3-D scenes was proposed by Alhazen (trans. 1989) about 1,000 years ago. According to Alhazen, in order for the magnitude of distance of an object to be perceived accurately, there has to be an array of “ordered, continuous bodies” between the object and the eyes. He mentioned the ground surface as an example of “ordered, continuous bodies” and proposed several experiments to show that the distance between two objects could not be perceived correctly if the ground surface between the two objects was not visible. Gibson (1946) also emphasized the importance of a continuous surface in organizing the perception of 3-D scenes. According to Gibson, although distance perception was traditionally regarded as judging the distance of specific objects, it is actually a continuum of terrain or surface that is perceived. Objects on or above the terrain are perceived relative to a background surface. The ground surface,

among all possible backgrounds, is of special importance. Gibson proposed that “The problem of three-dimensional vision, or distance perception, is basically a problem of the perception of a continuous surface which is seen to extend away from the observer . . . the ground is the basis of visual space perception both literally and figuratively” (Gibson, 1946, p. 420).

Bian, Braunstein, and Andersen (2005) investigated the relative effectiveness of different environmental surfaces—specifically, the ground surface, the ceiling surface, and the sidewalls—in indicating perceived relative distance of objects in 3-D scenes. We presented participants with a scene that included either two vertical posts between a ground surface and a ceiling surface, or two horizontal posts between two sidewalls. The optical contact (the contact between the image of an object and a background surface in a 2-D projection, as opposed to physical contact between the object and the background in a 3-D scene) between the two posts and the two surfaces was manipulated so that the two surfaces provided contradictory information about the relative distances of the posts from the participants (see Figure 1). The task of the participants was to judge which of the two posts appeared closer. When the two surfaces were a ground surface and a ceiling surface, participants showed a preference to make their judgments according to the optical contact information provided by the ground surface, which we referred

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Figure 1. Examples of stimuli used in Bian et al. (2005).

to as a *ground dominance effect*. When the surfaces were two sidewalls, participants showed no preference to either one. We also found that (1) this effect did not depend on the height of the posts in the image, (2) the ground dominance decreased as the scene was tilted away from a ground–ceiling orientation, and (3) this effect was not due to the vertical location on the posts where the judgments were made. We also demonstrated this effect in a real-world condition.

The reason for the ground dominance effect, however, has not been determined. Two possible explanations have been proposed, pertaining to two essential differences between the ground surface and the ceiling surface. The first difference is in the projections of ground and ceiling surfaces in 2-D images. If we define a ground surface as a surface slanted 90° , relative to frontal parallel, and viewed from above, and a ceiling surface as slanted 90° , and viewed from below, a ground surface recedes in depth from the bottom to the top of its projected image, whereas a ceiling surface recedes in depth from the top to the bottom of its projected image. (See Bian et al., 2005, for a discussion of slants other than 90° .) As suggested by Gibson (1946, 1950), the ground surface is universal, and supports most of the objects in the environment and the locomotion of animals. Our visual systems should be more adapted to a projection of a ground surface than to a projection of a ceiling surface, leading to a ground dominance effect when the ground surface and the ceiling surface provide contradictory information about the relative distance of objects in 3-D scenes. In recent years, a number of investigators have proposed similar ideas (Z. J. He, Wu, Ooi, Yarbrough, & Wu, 2004; McCarley & Z. J. He, 2000; Nakayama, Z. J. He, & Shimojo, 1995; cf. Sedgwick, 1986), and have examined how manipulating information on the ground surface could affect the perceived location of objects in 3-D scenes (see, e.g., Feria, Braunstein, & Andersen, 2003; Meng & Sedgwick, 2001, 2002; Ni, Braunstein, & Andersen, 2004, 2005, 2007; Sauer, Braunstein, Saidpour, & Andersen, 2002; Sinai, Ooi, & Z. J. He, 1998; B. Wu, Ooi, & Z. J. He, 2004).

Meng and Sedgwick (2001) proposed that objects lying on different surfaces are ultimately supported by the ground plane and are connected to each other through a series of hierarchical “nested” contact relations. They showed that such nested contact relations could be used by participants to determine the distance of objects accurately. However, as the contact relations became more complex, judged distance became less accurate, suggesting that the local spatial relations between objects and the surfaces supporting them were not fully integrated with the global spatial relations of the scene as a whole (Meng & Sedgwick, 2002). Similar results with stereoscopically perceived depth were obtained by Sedgwick, Gillam, and Shah (2004, 2005).

Recently, Ni et al. (2004, 2005, 2007) systematically examined the relative effectiveness of optical contact information and other cues, such as motion parallax, shadow, and occlusion, on perceived distance of objects in 3-D scenes. Overall, they found that (1) optical contact information dominated motion parallax when only one object was presented, whereas optical contact could be outweighed by a grouping effect with multiple objects moving rigidly (Ni et al., 2005); (2) the perceived distance of an object was determined both by optical contact information and by information provided by shadow, with shadow having a greater effect, especially in moving scenes (Ni et al., 2004); and (3) the addition of occlusion information limited the range of perceived distance of an object indicated by optical contact and motion parallax (Ni et al., 2007).

Sinai et al. (1998) found that with a gap or a change of texture on the ground surface, perceived distance was less accurate than when the ground surface was continuous. This discontinuity effect was also found by J. Wu, Z. J. He, and Ooi (2002) using virtual reality displays, and by Feria et al. (2003) using computer-simulated scenes. Z. J. He et al. (2004) proposed that the discontinuity effect results from a sequential surface integration process (SSIP), through which the ground surface is represented in the visual system. The SSIP hypothesis assumes that

the ground surface is perceived accurately only at near distance, where sufficient depth cues, such as vergence, binocular disparity, and so on, are present. As long as the texture gradient on the ground is homogenous, the visual system can integrate across further distances gradually and form an accurate representation of the ground. However, when a change of texture occurs, this integration process is disrupted and a new integration has to be initiated at the boundary. Since depth cues are not sufficient at far distances, the ground surface will be perceived as slanted, with its far end upward (a "frontal effect")—which is partly due to the intrinsic bias of the visual system—leading to an underestimation of distance. This integration process hypothesis was supported by Z. J. He et al. (2004). They found that when there was an occluding box between a participant and a target object on the ground, the distance of the target object was underestimated. However, when the participants had to integrate through a continuous surface by first walking blindly to another object to the side of the occluding box and then to the target object, or first to the target object and then to the side object, participants' performance was as accurate as when the occluding box was absent. B. Wu et al. (2004) found further support for the SSIP hypothesis by showing that perceived distance was more accurate with a larger field of view, especially in the vertical dimension, and that perceived distance was more accurate when scanning the ground surface from near to far rather than from far to near. Perceived distance on the ground surface was also found to be affected by wearing base-up prisms, which deviated the direction of light and thus changed the visual angle between an object and eye level (Ooi, B. Wu, & Z. J. He, 2001), and by having a local region providing perspective information (Sauer et al., 2002).

Using stereograms, Nakayama et al. (1995) demonstrated the importance of a visual surface representation in mediating the information picked up by lower-level visual processes and higher-level perceptual functions. They proposed that our adaptive perceptual system has to maximize the economy of representation in order to operate efficiently in the visual environment. A pattern or display that appears more frequently in a natural environment will be more efficiently encoded and thus be more likely to be perceived. McCarley and Z. J. He (2000) presented participants with three vertically stacked near-horizontal arrays of orange and green rectangular elements defined stereoscopically. Each array was composed of three rows of four coplanar elements. The elements were either slanted "top away," to form an implicit ground surface, or "bottom away," to form an implicit ceiling surface. The task of the participant was to search for an odd-colored element in the middle array. They found that participants responded faster when the elements formed an implicit ground surface than when the elements formed an implicit ceiling surface. In Experiment 2, they replaced the slanted elements with frontal-parallel elements to show that the ground-like surface advantage was not due to the different orientation of the elements between the ground-like

surface and the ceiling-like surface, or to the relative difficulty of establishing coplanarity between the ground-like surface and the ceiling-like surface. In Experiment 3, they blocked the orientation of the 3-D array, and in half of the trials allowed the participants to fixate and fuse achromatic ground-like or ceiling-like configurations before trial onset. (In this condition, elements changed color after the onset of the trial.) Again, they found a shorter response time (RT) with a ground-like surface than with a ceiling-like surface, demonstrating that this asymmetry was not due to prior knowledge of the surface orientation or to prior fusion of the surface.

Whereas the ground dominance effect could be due to the unique projection of the ground surface, it could, on the other hand, simply be a result of the positions typically occupied by the ground and ceiling surfaces in the visual field. That is, the ground surface is generally located in the lower part of the visual field (referred to as the LVF, hereafter), whereas the ceiling surface is generally located in the upper part of the visual field (referred to as the UVF, hereafter). As many studies have shown, a wide variety of visual tasks are processed better in the LVF than in the UVF.

For instance, S. He, Cavanagh, and Intriligator (1996) proposed that attentional resolution is greater in the LVF than in the UVF. In one of their experiments, participants were asked to judge whether the orientation of a circular patch of sinusoidal grating was 45° or 135°. The target grating was presented briefly (180 msec), either alone or with four distractor gratings aligned vertically with the target grating, one above it and three below it. They found that the accuracy rate dropped significantly when the target grating was crowded by distractor gratings, in comparison with when it was presented alone, which they referred to as a "crowding effect." Most importantly, they found that this effect was significantly greater in the UVF than in the LVF. If this asymmetry was due to the difference of attentional resolution between the LVF and UVF, they argued, a task requiring more focused attention should demonstrate an LVF advantage, whereas a task requiring little focused attention should show similar performance in both the LVF and UVF. Using a visual search task, they found an LVF advantage when the target was a simple feature conjunction (tilted "T" shape), whereas when the target was a feature (tilted bar), there was no difference between the LVF and UVF, which was consistent with their hypothesis.

Ellison and Walsh (2000) argued that the results in S. He et al. (1996) were attributable to properties of the stimuli used in their experiments, rather than to a difference in attentional resolution. Using a visual search task in which the target was either a feature (slash) or a feature conjunction (colored slash), they presented stimuli either across the whole visual field or restricted to the LVF or UVF. They found that when the stimuli occupied the whole visual field, there was no difference between the LVF and UVF, whereas when the stimuli were restricted to either the LVF or UVF, the participants were faster finding the target in the LVF. On the basis of these results, Ellison and

Walsh (2000) suggested that the LVF advantage existed only when the LVF was stimulated in isolation. However, Rezac and Dobkins (2004) measured visual discrimination thresholds for motion and orientation and found that when the target displays were presented alone, in a single quadrant, the LVF advantage was much smaller than when the target displays were presented with noise distractors in the other three quadrants.

This superior performance in the LVF in comparison with the UVF has been found in many other tasks, such as figure-ground segmentation (Rubin, Nakayama, & Shapley, 1996; Vecera, Vogel, & Woodman, 2002), intrasaccadic motion detection (Gysen, Verfaillie, & De Graef, 2002), and visually guided actions (Danckert & Goodale, 2001; see also Danckert & Goodale, 2003, for a review). Some visual evoked potential and magnetoencephalographic studies have found stronger signals in the occipital cortex when the LVF was stimulated (Fioretto et al., 1995; Portin, Vanni, Virsu, & Hari, 1999), suggesting a physiological basis for this LVF advantage.

In order to investigate which of the two distinctions between the ground surface and ceiling surface accounts for the ground dominance effect—the location in the visual field or the projection of the surface—we manipulated the vertical location of the ground surface and ceiling surface—that is, a ground surface could appear in the UVF, whereas a ceiling surface could appear in the LVF. In Experiment 1, we presented participants with a scene in which the ground surface and ceiling surface were either symmetrically positioned about a central fixation, or both were above or both were below fixation. Two vertical posts were presented between the two surfaces; their optical contact with the two surfaces was manipulated to provide contradictory layout information. In Experiments 2 and 3, only one surface, either the ground surface or the ceiling surface, was present in each trial, and there were either two vertical posts (Experiment 2) or two red dots (Experiment 3) on the surface. The surface was placed in various locations in the visual field. The task of the participants in all three experiments was to decide which of the two objects (posts in Experiments 1 and 2 and red dots in Experiment 3) was closer.

We hypothesized that, if the ground dominance effect was due to the unique projection of the ground surface, we should find a ground dominance effect independent of the ground surface's location in the visual field. If the ground dominance effect was due to an LVF advantage, we should find a decrease in the ground dominance effect as the ground surface was moved from the bottom to the top of the visual field. It is also possible that the two explanations are not mutually exclusive. That is, they might both account for the ground dominance effect.

EXPERIMENT 1 Two Surfaces

Method

Participants. The participants were 14 undergraduate students at the University of California, Irvine, ranging in age from 19 to 26,

who received course credit for their participation. All were naive regarding the purpose of the experiment and all had normal or corrected-to-normal visual acuity (20/40 measured with a Snellen eye chart).

Stimuli. The stimuli were computer-generated 3-D scenes composed of a random checkerboard-textured ground surface and ceiling surface and two vertical posts with a texture of vertical stripes. The two surfaces were tilted 15° either clockwise or counterclockwise. The simulated distances from the participant to the closer and more distant ends of the surfaces were 571 and 2,000 cm, respectively. (The calculation of the scene dimensions was based on an eye height of 120 cm.)

Two textured posts, centered horizontally, each with dimensions of $20 \times 176 \times 10$ cm, were positioned at 1,200 cm from the observer. The horizontal separation between the posts was 220 cm. One of the posts was in contact with the ground in the simulation, and there was a gap between its top surface and the ceiling. It was thus in optical contact with the ceiling in the image, but not in physical contact with the ceiling in the simulation. The other post was in contact with the ceiling, but there was a gap between its bottom surface and the ground, so that it was in optical contact but not in physical contact with the ground (see Figure 2). The simulated location in depth was the same for both posts, but their optical contact positions on the two surfaces had a depth separation of 647 cm. Thus, ground and ceiling contact provided contradictory information about the relative positions of the posts in the scene.

Design. Two independent variables were manipulated. The first variable, the vertical position of the surfaces relative to fixation, had three levels: (A) both surfaces below fixation, (B) one surface below fixation and one above fixation, and (C) both surfaces above fixation (see Figure 2). Three control conditions were included with displays that had twice the vertical extent as those in the experimental conditions: (D) The ground surface and the ceiling surface were moved toward the bottom of the screen so that the ceiling surface was closer to the center of the screen than to the ground; (E) the two surfaces were positioned symmetrically around the center of the screen; and (F) both surfaces were moved toward the top of the screen so that the ground surface was closer to the center of the screen than to the ceiling surface. The purpose of the control conditions was to examine the effects of varying eccentricity of the ground and ceiling surfaces when they were in their typical locations in the visual field (LVF for the ground surface and UVF for the ceiling surface). The projected ground and ceiling surfaces did not vary with their heights in the visual field. Slight changes in the projections would occur in direct vision if the surfaces remained at 90° slants but were raised or lowered relative to the line of sight. Instead, the same projected ground and ceiling surfaces were shown at each height in order to study the effect of height in the visual field without a concomitant change in the projected surfaces. Ground dominance has been demonstrated in direct vision (Bian et al., 2005; Dilda, Creem-Regehr, & Thompson, 2005), but it is difficult to match the ground and ceiling displays in real-world stimuli.

The other independent variable was which post (left or right) had the closer optical contact with the ground. To keep the height of the two posts in the image equal, the direction of tilt of the surfaces was determined by which post had the closer optical contact with the ground. The other post had closer optical contact with the ceiling. Thus, there were a total of 3 (surface location) $\times$ 2 (post with closer optical contact with the ground) = 6 experimental conditions and 3 (surface location) $\times$ 2 (post with closer optical contact with the ground) = 6 control conditions.

The dependent variable was the proportion of each participant's judgments consistent with the optical contact of the two posts with the ground surface. A higher proportion means that participants were more frequently making their judgment about which post appeared closer in accordance with the optical contact with the ground surface. We also recorded participants' RTs to determine whether there was an effect of surface type on response latency, as found in

Figure 2. Examples of the stimuli in Experiment 1: (A) both surfaces below central fixation, small display, (B) ground surface below fixation and ceiling surface above fixation, small display, (C) both surfaces above central fixation, small display, (D) ceiling surface closer to central fixation than ground surface, large display, (E) two surfaces equal in distance to central fixation, large display, (F) ground surface closer to central fixation than ceiling surface, large display.

our previous study (Bian et al., 2005). Although participants were not instructed to respond as soon as possible, average response latencies were under 1 sec.

Apparatus. The displays were presented on a 21-in. (53-cm) flat screen CRT monitor with a pixel resolution of $1,280 \times 1,024$, controlled by a Windows 2000 workstation. The dimensions of the display on the monitor were 25.2×8.4 cm, subtending a visual angle of $20.0^\circ \times 6.7^\circ$, for the small displays, and 25.2×16.8 cm, subtending a visual angle of $20.0^\circ \times 13.4^\circ$, for the large displays. A 19-cm-diameter collimating lens, which magnified the images by approximately 19%, was located between the participant and the monitor. The purpose of the collimating lens was to remove accommodation as a flatness cue and thus increase perceived depth in the 2-D projections of the 3-D scenes. The distance between the eyes and the lens was approximately 10 cm and the distance from the eyes to the monitor was 85 cm. A chinrest was mounted at a position appropriate to this viewing distance. The participants used a joystick to respond and to initiate the next trial.

Procedure. The experiment was run in a darkened room. Each participant viewed the monitor binocularly through the collimating lens with his or her head in the chinrest. On each trial, a white cross first appeared in the center of the screen. The participants were required to fixate the cross and press the trigger button of the joystick. The cross was then replaced by a white digit, which was either an odd number (1, 3, or 5) or an even number (2, 4, or 6). The digits were presented within an area of 0.88×1.17 cm, or a visual angle of $0.70^\circ \times 0.94^\circ$. It was expected that participants would have to fixate the digits to identify them accurately. (Klein, Berry, Briand, D'Entremont, & Farmer, 1990, found a drop in accuracy from 97% to 83% with a change in distance from fixation from 0.7° to 2.5° for their "good reader" group in a 10-letter identification task with let-

ters subtending visual angles of about $0.63^\circ \times 0.85^\circ$.) After 75 msec, the digit disappeared and a scene containing a ground surface, a ceiling surface, and two vertical posts was presented. After 250 msec, the scene was replaced by a black screen (see Figure 3). The task of the participants was to determine which of the two posts, the left one or the right one, appeared to be closer, and to bend the joystick in the corresponding direction. Participants were instructed to make these judgments only when they saw an odd (or even, for half of the participants) digit before the presentation of the scene (go trials). They were asked not to make a response when they saw an even (or odd) digit (no-go trials). The purpose of using a go/no-go paradigm was to keep the participants fixated at the center of the screen. The participants had up to 4 sec to make a decision. If they failed to make a response in a go trial within 4 sec, that trial was repeated at the end of the block and was counted as a miss. In a no-go trial, if the participants did not make a response within 4 sec (which was the correct action), the next trial would begin. However, if a participant responded in a no-go trial, that trial was counted as a false alarm. Any participant making errors (the total of misses and false alarms) in more than 10% of the total number of trials was eliminated from the data analysis. The short display time of the scene, 250 msec, was intended to prevent participants from changing their fixation during the trial.

Each of the 12 conditions (6 experimental + 6 control) was repeated nine times in go trials and four times in no-go trials. In order to prevent participants from judging the relative distance of the two posts by simply responding to the tilt direction of the surfaces, each combination was repeated in an additional 3 trials in which the relation between the optical contact of the two posts with the ground and the tilt direction of the surfaces was opposite to that in the experimental trials, making a total of 192 trials. The 192 trials were evenly

Figure 3. Example of the sequence of a trial in Experiment 1.

divided into three blocks with 64 trials in each, with 6 practice trials inserted at the beginning of each block. These experimental blocks were preceded by a practice block chosen randomly from the experimental blocks.

Results and Discussion

Data from 2 participants were excluded from the analysis, 1 for not following the instructions correctly and the other for making too many errors ($>10\%$). On average, the proportion of judgments consistent with optical contact with the ground surface was highest (.86) in Condition B, in which the two surfaces were positioned above and below fixation, intermediate (.74) in Condition C, in which the two surfaces were both above central fixation, and lowest (.66) in Condition A, in which both surfaces were below fixation (see Figure 4). All of these proportions were significantly different from chance (.50, $p < .01$, two-tailed binomial test). A two-way ANOVA with repeated measures revealed a significant main effect of the location of the surfaces [$F(2,22) = 5.05$, $p < .05$]. A Tukey post hoc test found a significant difference ($p < .05$) between Condition B and Condition A. No other significant effects were found. These results show ground dominance (proportions of choice consistent with the ground surface greater than .5) for all three visual field positions. The ground dominance effect was lowest with both surfaces below fixation. This may have occurred because the ceiling surface in this condition was between fixation and the ground. In the control conditions with a larger display, the proportions were .78 for the lower surface position (D), .85 for the middle position (E), and .88 for the upper position (F). No significant differences were found between the three control conditions. In control Condition D, with both surfaces displaced toward the

LVF, the entire ceiling surface was not between fixation and the ground surface. This may account for the lack of a significant reduction in the proportion of choices made in accordance with the ground surface in that condition, in contrast to the significant reduction found for Condition A.

The RTs for the three main conditions were 849 msec for Condition A, 738 msec for Condition B, and 887 msec for Condition C (see Figure 5). A two-way ANOVA with repeated measures found a significant main effect of surface location [$F(2,22) = 10.95$, $p < .001$]. A Tukey post hoc test found that the RT for Condition B was significantly shorter ($p < .01$) than those for Conditions A and C. No other effects were significant. In the three control conditions with a larger display, the RTs were 761 msec for the lower condition (D), 729 msec for the middle condition (E), and 774 msec for the upper condition (F). No significant differences were found between the three control conditions.

EXPERIMENT 2 Single Surface

In two of the three conditions examined in Experiment 1, the ground surface and the ceiling surface were not at equal distances from central fixation. That is, when the two surfaces were both below fixation, the ceiling surface was closer to fixation than the ground surface, whereas when the two surfaces were both above fixation, the ground surface was closer to fixation than the ceiling surface. Although the control conditions showed no effect of a difference in proximity to the center, they did not control any possible effect of having one surface between fixation and the other surface, when both surfaces were

Figure 4. The effect of the location of the surfaces on the proportion of judgments based on ground contact information in Experiment 1. Error bars represent ± 1 SE after centering. (In centering, the difference between the mean across all participants and the mean for an individual participant is added to each of that participant's scores before computing the standard errors for conditions, so that the standard errors are not inflated by individual differences unrelated to the conditions.) LVF, lower visual field; UVF, upper visual field.

in the upper or lower visual field. In order to control the proximity of the surfaces to fixation and eliminate the effects of having one surface between fixation and another surface, we presented only one surface on each trial in Experiment 2.

Method

Participants. The participants were 15 undergraduate students at the University of California, Irvine, ranging in age from 18 to 26, who received course credit for their participation. All were naive regarding the purpose of the experiment and all had normal or corrected-to-normal visual acuity.

Stimuli. The stimuli were similar to those in Experiment 1, with the exception that only one surface was presented on each trial. Examples of the stimuli are shown in Figure 6.

Design. There were three independent variables: (1) the surface that was present, either a ground plane or a ceiling plane; (2) the location of the surface relative to fixation, either below, at, or above fixation; and (3) which post (left or right) had the closer optical contact with the surface presented. Thus, there were a total of 2 (surface type) $\times 3$ (location in visual field) $\times 2$ (post with closer optical contact with the surface presented) = 12 conditions.

Each of the 12 conditions was repeated nine times for go trials and four times for no-go trials. In order to prevent participants from judging the relative distance of the two posts by simply responding to the tilt direction of the surfaces, each combination was repeated in an additional 3 trials in which the relation between the optical contact of the two posts with the ground and the tilt direction of the surfaces was opposite to that in the experimental trials, making a total of 192 trials. The 192 trials were evenly divided into three blocks with 64 trials in each, and 6 practice trials were inserted at the beginning of each block. These experimental blocks were preceded by a practice block chosen randomly from the experimental blocks.

Apparatus and Procedure. The procedure was the same as in Experiment 1. A go/no-go paradigm was used. The participants were asked to determine which of the two posts appeared closer, by bending the joystick handle to the left or right. The RT and the propor-

tion of judgments consistent with the surface that was present were measured.

Results and Discussion

The data from 2 participants were excluded because they made more than 10% errors in the go/no-go task. The proportion of judgments consistent with the surface present at each location in the visual field is shown in Figure 7. As the figure shows, this proportion was higher for the ground surface than for the ceiling surface when the surfaces were presented at the middle or top of the display. However, when the surfaces were presented at the bottom of the display, the proportion was higher for the ceiling surface than for the ground surface. A three-way ANOVA with repeated measures confirmed this interaction between the surface and the location in visual field [$F(2,24) = 7.85, p < .01$]. We also found a significant main effect of surface [$F(1,12) = 9.69, p < .01$], showing that the proportion of judgments consistent with the ground surface was higher overall than the proportion of judgments consistent with the ceiling surface. There was also a main effect of location in the visual field [$F(2,24) = 7.06, p < .01$]. The proportion of responses consistent with the ground surface was significantly higher when the surface was in the middle location than when it was in the bottom location or the top location (Tukey test, $p < .05$). No other significant effects were found.

At each location, the RT to the ground surface was faster than that to the ceiling surface, as can be seen in Figure 8. A three-way repeated measures ANOVA found a significant main effect of surface type [$F(1,12) = 6.59, p < .05$]. No other significant effects were found for the RTs.

Figure 5. The effect of the location of the surfaces on RT in Experiment 1. Error bars represent $\pm 1 SE$ after centering.

Although the results from the RTs showed an overall advantage of responding to the ground surface over the ceiling surface, the results from the proportion of judgments consistent with the surface that was presented suggested that the ground dominance effect depends both on the type of surface and on its location in the visual field:

When the surface was at the middle or top of the visual field, participants were more likely to use the information provided by a ground surface than that provided by a ceiling surface, whereas when the surface was at the LVF, participants were equally likely to use the information provided by the two types of surfaces.

Figure 6. Examples of the stimuli in Experiment 2: (A) ground surface below central fixation, (B) ground surface at central fixation, (C) ground surface above central fixation; (D) ceiling surface below central fixation, (E) ceiling surface at central fixation, (F) ceiling surface above central fixation.

Figure 7. The effect of the location of surface on the proportion of judgments based on optical contact information in Experiment 2. Error bars represent $\pm 1 SE$ after centering.

EXPERIMENT 3 Equal Eccentricity of the Optical Contacts on Ground and Ceiling

In Experiment 2, the distances between the surface and fixation were equated across conditions, but the distances between the optical contact locations of the posts and fixation depended on the type of surface and its position. In Experiment 3, we equated the distances between the optical contact points and fixation for matched positions of the ground and ceiling surfaces above and below fixation. In order to equate these positions and increase the number of possible positions, the two posts were replaced by two red disks on the surface.

Method

Participants. The participants were 21 undergraduate students at the University of California, Irvine, ranging in age from 18 to 28, who received course credit for their participation. All were naive regarding the purpose of the experiment and all had normal or corrected-to-normal visual acuity.

Stimuli. The stimuli differed from those in Experiment 2 in two respects: (1) the two posts were replaced by two red disks, and (2) in each location of the visual field, the eccentricity of the optical contact between the disks and the surface was the same for both the ground and ceiling surfaces. The vertical distances from the center of the disks to central fixation, measured at the monitor, were 0, ± 4.34 , and ± 8.67 cm, subtending visual angles of 0° , 3.5° , and 6.9° , respectively. Examples of the stimuli are shown in Figure 9.

Design. Three independent variables were manipulated: (1) the surface that was present, either a ground surface or a ceiling surface;

Figure 8. The effect of location of the surfaces on RT in Experiment 2. Error bars represent $\pm 1 SE$ after centering.

(2) the location of the surface relative to central fixation, either at the bottom, middle bottom, middle, middle top, or top of the visual field; and (3) which dot (left or right) had closer optical contact with the surface presented. Thus, there were a total of 2 (surface type) $\times$ 5 (location in visual field) $\times$ 2 (dot with closer optical contact with the surface) = 20 conditions.

Each condition was repeated six times for go trials, two times for no-go trials, and another two times for control trials (in which the relation between tilt and relative distance was reversed), making a total of 200 trials. The 200 trials were divided into three blocks, with 67 trials in the first two blocks and 66 trials in the last block. Six practice trials were inserted at the beginning of each block. These experimental blocks were preceded by a practice block chosen randomly from the experimental blocks.

Apparatus and Procedure. The procedure was the same as in Experiments 1 and 2. A go/no-go paradigm was used. The participants were asked to indicate which of the two disks appeared closer by bending the joystick handle to the left or right. The RTs and the proportion of judgments consistent with the surface that was present were measured.

Results and Discussion

The data from 3 participants were excluded because they exceeded the criterion of 10% errors in the go/no-go task. The proportion of judgments that were consistent

with the surface present for each of the five locations in the visual field is shown in Figure 10. At each of the five locations, the proportion of judgments consistent with the ground surface was higher than that consistent with the ceiling surface. This was confirmed by a main effect of surface type [$F(1,17) = 28.48, p < .0001$] in a three-way ANOVA with repeated measures. We also found a significant interaction between surface type and location in the visual field [$F(4,68) = 2.88, p < .05$], suggesting that the ground surface advantage varied across different locations: When the surface was in the lower visual field, the ground surface advantage was smaller than when the surface was in the middle or upper visual field. In order to examine whether there was an overall difference between LVF and UVF conditions, we conducted a planned comparison between responses averaged across all LVF conditions and responses averaged across all UVF conditions, combining the ground surface and the ceiling surface results at each location. The difference between the locations was not significant [$F(1,17) = 1.09, p = .31$].

Figure 11 shows that the RT to the ground surface was faster than that to the ceiling surface at each location in the visual field. A three-way repeated measures ANOVA

Figure 9. Examples of stimuli in Experiment 3: (A–E) ground surface from bottom to top of the visual field; (F–J) ceiling surface from bottom to top of the visual field; (K) enlarged view of the surface in (I). The red ellipses are shown as black ellipses with white borders.

Figure 10. The effect of the location of surfaces on the proportion of judgments based on optical contact information on the surface present in Experiment 3. Error bars represent ± 1 SE after centering.

found a significant difference between the two surface types [$F(1,17) = 10.69, p < .01$]. A planned comparison between UVF and LVF found a significant UVF advantage [$F(1,17) = 7.82, p < .05$], which was not consistent with previous studies showing an LVF advantage (e.g., Ellison & Walsh, 2000; Gysen et al., 2002). Figure 11 shows that the RT for the ground surface was almost the same in the LVF and UVF (744 and 641 msec for bottom and middle-bottom locations vs. 725 and 656 msec for top and middle-top locations). However, the RT for the ceiling surface was consistently longer in the LVF than in the UVF (879 and 808 msec for bottom and middle-bottom locations vs. 802 and 753 msec for top and middle-top locations). This suggests that moving a surface from its

typical location only affects the ceiling surface. When a ground surface was moved to the UVF, people could respond as fast as when it was in the LVF.

There was also a main effect of location in the visual field [$F(4,68) = 8.64, p < .05$], suggesting that the response was faster when the surfaces were presented close to central fixation than when the surfaces were presented farther away from fixation. Moreover, we found a two-way interaction between the dot with closer optical contact with the surface presented and surface type [$F(1,17) = 6.17, p < .05$], and a three-way interaction between the dot with closer optical contact with the surface presented, surface type, and location in the visual field [$F(4,68) = 2.56, p < .05$]. That is, at each location, the RT to the ground surface

Figure 11. The effect of location of the surfaces on RT in Experiment 3. Error bars represent ± 1 SE after centering.

was about the same whether the optical contact information indicated that the right dot or the left dot was closer. However, RT to the ceiling surface was longer when the optical contact information indicated that the left dot was closer, and the difference increased as the ceiling surface was moved away from central fixation.

GENERAL DISCUSSION

In this series of experiments, we investigated the reason for the dominance effect of the ground surface over the ceiling surface in indicating the relative distance of objects in 3-D scenes. Two hypotheses were proposed: If ground dominance was due to inherent differences between the ground surface and the ceiling surface, we should find a ground surface advantage in all locations in the visual field. If, however, it was due to an LVF advantage, we should see an advantage for the surface in the LVF, regardless of the type of surface.

In Experiment 1, we presented participants with either two surfaces above central fixation or below central fixation, or one above and one below fixation. In all three conditions, we found that participants more frequently used the optical contact information on the ground surface to determine which of two posts was closer. We also found that the proportion of judgments consistent with the ground surface was higher when the two surfaces were in their regular locations in the visual field than when one of the surfaces was displaced. In Experiment 2, with only one surface presented on each trial, we found a ground surface advantage in the middle and upper visual field, but not in the lower visual field. In Experiment 3, with the eccentricity of the optical contact on the two surfaces equated in each of five locations in the visual field, we found a ground surface advantage in all locations. This is consistent with the hypothesis that ground dominance is related to the type of surface. We also found that the ground surface advantage was greater in the middle and upper visual fields than in the lower visual field, suggesting a minor effect of location in the visual field as well. The RT to the ground surface was shorter than to the ceiling surface and was shorter to the surfaces presented in the UVF than to the surfaces in the LVF.

As a ground surface recedes in depth, the farther away an object is on the ground, the higher it projects onto the retina, whereas, as a ceiling surface recedes in depth, the farther away an object is, the lower it projects onto the retina. Although the two surfaces studied were symmetrically reversed optical patterns, perceptually they were not treated equally. Our results showed that information on a ground surface is usually given more weight than information on a ceiling surface when determining the relative distance of objects in a scene. Such results are not unexpected, considering that the ground surface bears more ecological importance than the ceiling surface. As Gibson (1946, 1950) noted, the ground surface is universal and provides support for locomotion of most animals. Also, since most objects are connected to the ground surface

either directly or through a series of “nested” contact relations (Meng & Sedgwick, 2001), most of our behaviors are conducted with the ground or a surface parallel to it as the background surface. Thus, it is quite possible that our visual system is adapted to process information on the ground more efficiently or with a higher priority. This has been confirmed by McCarley and Z. J. He (2001), who used stereoscopic displays and showed that visual search was faster when the objects were in a ground-like arrangement than when the objects were in a ceiling-like arrangement. Our results are also consistent with Helmholtz’s (1910/1962) likelihood principle, which indicates that a retinal image should be perceived as being produced by the most frequently occurring external stimulus.

Location in the visual field is important in determining the size of the ground surface advantage, as can be seen from Figure 10: In the lower visual field, the ground surface advantage was not as great as that in the middle or upper visual field. Although this is probably because the information on the ceiling surface is more easily processed when it is located in LVF than when it is located in UVF, such perceptual improvement is at the cost of RT. Figure 11 shows that participants spent longer making their judgments when the ceiling surface was in LVF than when it was in UVF, whereas the RT to the ground surface did not vary greatly in different locations in the visual field. This suggests that responses to the ground surface are less variable than those to the ceiling surface, which is consistent with the results of a recent study by Dilda et al. (2005), who compared judged distance on the ground surface and the ceiling surface. This finding, that the RT to the ground surface was less dependent on its location in the visual field than the RT to the ceiling surface, may explain why we did not obtain an overall LVF advantage, as found in previous studies (e.g., Gysen et al., 2002; S. He et al., 1996). Another possible reason is that we did not include a time restriction in the instructions, which is different from previous studies (e.g., S. He et al., 1996).

An important issue for future research would be to determine whether this ground surface advantage generalizes to other visual tasks. If the visual system is more adapted to the ground surface, could people search faster on the ground surface than on the ceiling surface? Could people judge distance more accurately on the ground surface than on the ceiling surface? McCarley and Z. J. He (2000) showed a ground surface advantage in visual search using stereoscopic displays, and it would be useful to extend this research to ground and ceiling surfaces represented by other types of depth information. A recent study by Dilda et al. (2005) compared distance judgments on the ground surface and on the ceiling surface. They found that distance judgments were accurate on both surfaces, but variability was greater when the target was located on the ceiling than when the target was on the ground. However, their experiments were conducted in a real-world environment, in which viewing of the sidewalls and the ground surface was not restricted while judging the distance of an object on the ceiling surface, and the ground surface and

the ceiling surface were not comparable in texture gradients. Further research is needed to compare the accuracy of distance judgments for ground and ceiling surfaces.

Overall, our results demonstrated that the dominance effect of the ground surface over other environmental surfaces, especially the ceiling surface, in determining perceived relative distance of objects in 3-D scenes, is mainly due to characteristics of the ground surface per se, rather than to the different locations of the ground surface and the ceiling surface in the visual field, although the location in the visual field had a minor effect on the size of the ground surface advantage. Our results concur with those of an increasing number of studies in recent years demonstrating the importance of the ground surface in scene perception (e.g., Feria et al., 2003; Meng & Sedgwick, 2001, 2002; Ni et al., 2004, 2005, 2007; Ooi et al., 2001; Sinai et al., 1998; B. Wu et al., 2004). Future studies are needed to examine the relative influence of type of surface (ground vs. ceiling) and location in the visual field in other visual tasks, such as visual search and absolute and relative distance judgments.

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