Research Report

SEEING MOUNTAINS IN MOLE HILLS: Geographical-Slant Perception

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Abstract—*When observers face directly toward the incline of a hill, their awareness of the slant of the hill is greatly overestimated, but motoric estimates are much more accurate. The present study examined whether similar results would be found when observers were allowed to view the side of a hill. Observers viewed the cross-sections of hills in real (Experiment 1) and virtual (Experiment 2) environments and estimated the inclines with verbal estimates, by adjusting the cross-section of a disk, and by adjusting a board with their unseen hand to match the inclines. We found that the results for cross-section viewing replicated those found when observers directly face the incline. Even though the angles of hills are directly evident when viewed from the side, slant perceptions are still grossly overestimated.*

In several recent studies, we have shown that people's conscious perception of the slant of hills is greatly overestimated even though their visually guided actions show little evidence of this bias (Bhalla & Proffitt, 1999; Creem & Proffitt, 1998; Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Conscious perceptions of slant were assessed in two ways. Participants gave verbal judgments, and they also adjusted the size of a pie-shape segment of a disk so that it corresponded to the cross-section of the hill. Figure 1 depicts the disk device. The visually guided action was an adjustment of a palm board to correspond to the slant of the observed hill. Overestimations on the first two measures were consistent and huge. A 10° hill, for example, was typically judged to be about 30° when assessed by verbal reports and disk adjustments.[1] The palm-board settings were relatively accurate.

In all of these studies, participants viewed the hills head-on, and thus, their perspective on each hill's slant provided a view of its pitch. The task of setting a cross-section with the disk required that they translate observed pitch into an adjustment of apparent roll. We wondered whether the conscious perception of slant would change—be more accurate—if assessments were made while participants looked at the sides of hills. There are good reasons to suspect that this might be so. Consider a situation in which participants view the side of a hill that has a well-specified horizontal reference, as shown in Figure 2a. Viewed from this perspective, the hill's cross-section in relation to the horizontal is robustly specified. In the disk-adjustment task, participants could simply line up the bottom edge of the pie shape with the horizontal and the top edge with the hill.

In the following experiments, we found that hills are overestimated to approximately the same degree whether people observe them head-on or to the side. This is puzzling for at least two reasons. First, people know what angles look like. In a previous study, when we asked participants to set cross-sections with the disk to a variety of angles, we found that they were quite accurate in doing so (Proffitt et al., 1995). Second, when viewing a hill in cross-section, an observer could adjust the disk accurately by lining up the two edges of the pie section to lines in the visual scene. Although our findings are perplexing, we have argued in our previous reports, and do so again in the General Discussion of this one, that the conscious overestimation of geographical slant is adaptive and that the veracity of perception should be evaluated relative to pragmatic as opposed to strictly geometric criteria.

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1. It is not the case that people are intrinsically inaccurate in their judgments of slant. Stevens (1983) showed that people were accurate to within a few degrees when asked to match the slants of two small-scale physical surfaces viewed in close proximity.

EXPERIMENT 1: REAL HILLS VIEWED FROM THE SIDE

Method

Participants

Thirty members of the University of Virginia community participated (12 male, 18 female). They were stopped as they passed by the experimenter, who was standing near the hill. All participants were naive to the purposes of the experiment and had not participated in any prior slant experiments. None had any apparent locomotor problems.

Stimuli

Two different views of one hill on the grounds of the University of Virginia were used in the study. The inclines were 24° and 34° as measured by a Suunto clinometer having an accuracy of 0.5°. Performance was compared with our normative data (Proffitt et al., 1995) for the same hill measuring 31°.

Apparatus

The participants reported their judgments using verbal, visual, and haptic measures. The visual measure used a disk consisting of an adjustable angle representing the cross-section of the inclination of a hill. A protractor was mounted at the back of the disk, which allowed the experimenter to determine the angle set by the participant. Participants were free to hold the disk in any orientation, and typically they held it approximately perpendicular to their line of sight. They adjusted the disk to the cross-section that they thought best represented the angle of inclination of the hill.

The haptic estimations were reported using a tilt board with a flat palm rest that could be adjusted to match the inclination of the hill. There was a protractor on the side of the board, concealed from the participants, which allowed the experimenter to determine the angle they set. The tilt board was mounted on a tripod whose height was adjusted to slightly above waist level for each participant. The participants were asked to match the tilt board to the slant of the hill as if they were placing their hand on the incline of the hill. The tilt board

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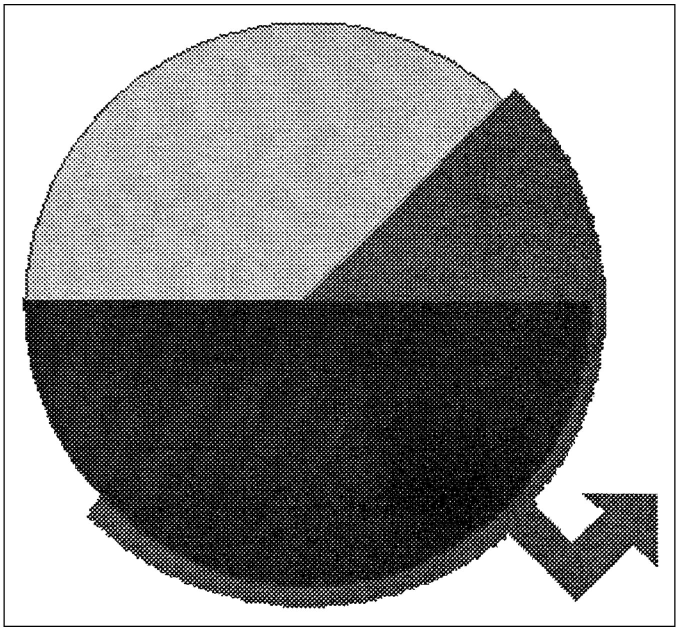

Fig. 1. The disk device used to give visual geographical-slant judgments.

was placed to the side of the participants, and they always adjusted it with their dominant hand. They were not permitted to look at their hand while making the adjustments.

Procedure

Each participant viewed only one hill (24°, $n = 15$; 34°, $n = 15$). Participants viewed the hill binocularly from the side while standing on steps adjacent to the hill (see Figs. 2a and 2b). They were instructed to look at the side of the hill and to judge the angle of inclination of the hill with respect to the horizontal, using the three measures, verbal, visual, and haptic. The order of judgments was counterbalanced and assigned randomly. The experimenter recorded the responses on paper. Feedback was not given.

Results and Discussion

Figure 3 shows the data from Experiment 1 along with the normative data (Proffitt et al., 1995) for the 31° hill. Overall, as the figure shows, participants' slant estimations were similar whether the hill was viewed from the side or the front. The portion of the normative data set used in this analysis consisted of judgments from 30 participants. A 3 (hill) × 3 (measure) analysis of variance (ANOVA) was performed on the combination of the present data set and the normative data set, with measure as a within-subjects factor and hill as a between-subjects factor. As expected, the analysis revealed a significant effect of measure, $F(2, 114) = 102.88$, $p < .001$. Simple planned contrasts revealed that both the verbal measure, $F(1, 59) = 135.59$, $p < .001$, and the visual measure, $F(1, 59) = 151.69$, $p < .001$, were different from the haptic measure. Scheffé post hoc comparisons indicated that neither the cross-section judgments for the 24° hill nor the cross-section judgments for the 34° hill were different from the front-view judgments for the 31° hill ($p = .46$ and .19, respectively). Strikingly, despite the fact that in the 24° view, participants faced directly toward a parking garage that provided clear 90° angles (see Fig. 2a), verbal and visual measures remained highly overestimated. Even more notably, the visual measure, which could involve simply matching the cross-section view on the disk to the view of the hill, was still consistently overestimated.

Individual t tests were conducted for the three hills (normative and two side views) to assess the accuracy of the estimations. For the front view, verbal and visual measures were significantly greater than the actual incline, $t(29) = 8.06$, $p < .001$, for the verbal measure and $t(29) = 8.03$, $p < .001$, for the visual measure; in contrast, the haptic estimation was not different from the actual incline, $t(29) = -1.7$, $p = .10$. We found the same pattern for the 24° side view, $t(14) = 8.03$, $p < .001$, for the verbal measure; $t(14) = 7.55$, $p < .001$, for the visual measure; $t(19) = -0.197$, $p = .49$, for the haptic measure. For the 34° side view, all three measures were different from the actual incline, $t(14) = 3.23$, $p < .01$, for the verbal measure; $t(14) = 2.83$, $p < .02$, for the visual measure; $t(14) = -2.82$, $p < .02$, for the haptic measure. All of the measures for the 34° side view followed the pattern of responses for the other two views, but the haptic estimations were slightly underestimated. This haptic underestimation is similar to what we found previously for larger hills (Proffitt et al., 1995).

EXPERIMENT 2: VIRTUAL HILLS VIEWED FROM THE SIDE AND FRONT

Experiment 1 indicated that estimations given when viewing a hill from the side are similar to those given when viewing the hill from the front for a real hill of about 30°. In Experiment 2, we examined this effect more closely using 12 different slants in virtual reality (VR).

Method

Participants

Twenty-four University of Virginia students participated (10 male, 14 female) as part of a requirement for an introductory psychology course. All had normal or corrected-to-normal vision. They were naive to the purposes of the experiment and had not participated in any prior slant experiments. None had any apparent locomotor problems.

Stimuli

Twelve hills ranging from 5° to 60°, in 5° increments, were simulated in VR. For the side viewpoint, the observer stood on a 2- × 2-m surface, 0.9 m above ground level, 6.5 m to the left of the hill's center, and 0.65 m behind the base of the hill (see Figs. 4a and 4b for an outsider's and the observer's perspective, respectively). For the front viewpoint, the observer stood at the hill's center, facing the incline. Each display consisted of a grassy hill with a gray cobblestone road running up the middle. The observer and the hill were placed on a large surrounding ground plane with the horizon clearly in view against rolling hills and a cloudy, blue background. Each hill was 30 m wide, with the road covering the central 10 m. A virtual tilt board was visible, placed in the corresponding location of the tilt board in the real world. The distance along the visual surface of the hill was kept constant at 100 m; the height of the hill and depth of the hill varied as a function of the slant angle. Two objects were placed on the hill: a car and a chicken. A virtual village with several colonial houses and build-

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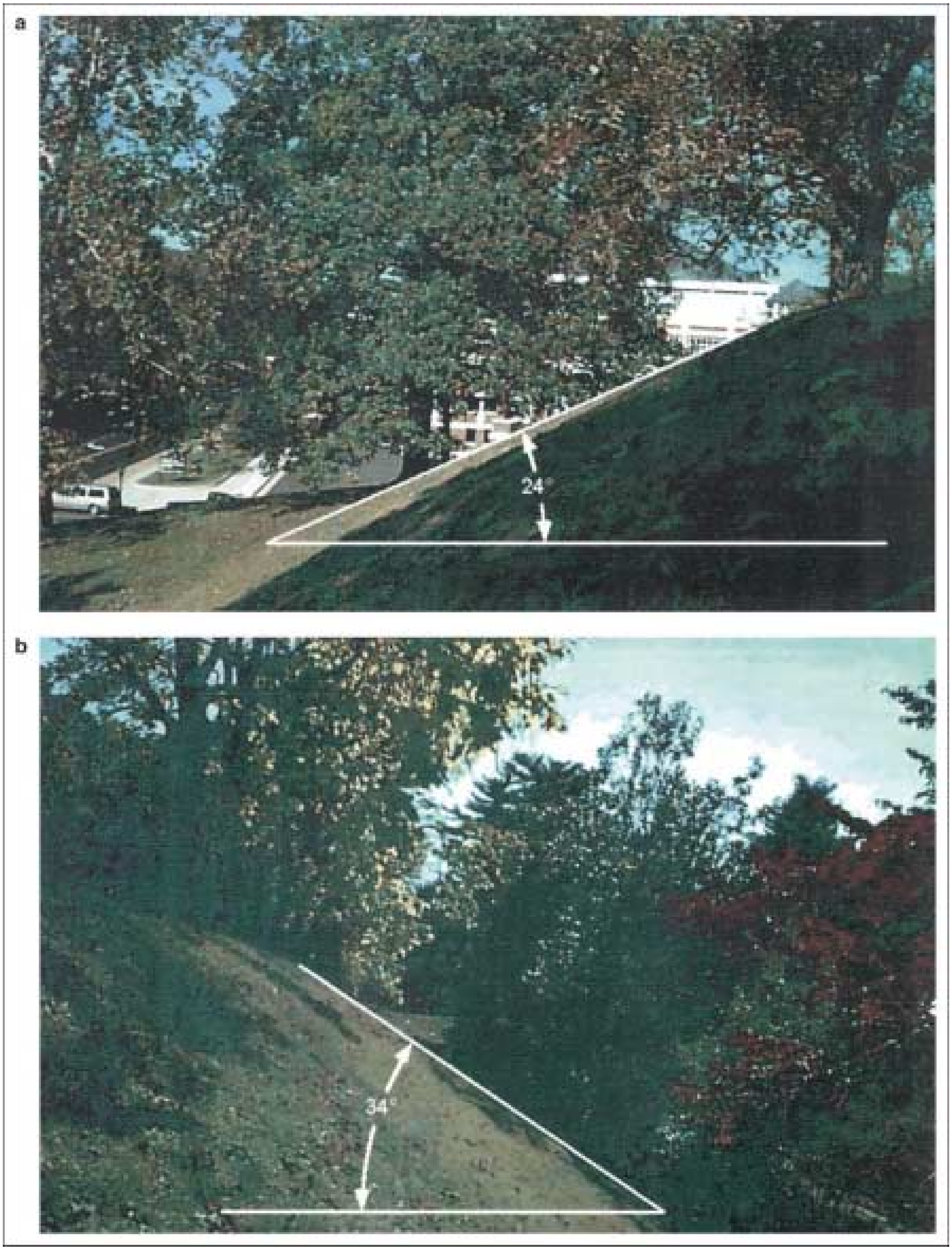

Fig. 2. The real hill viewed from the side in two different directions: (a) the 24° hill facing the parking garage and (b) the 34° hill facing trees.

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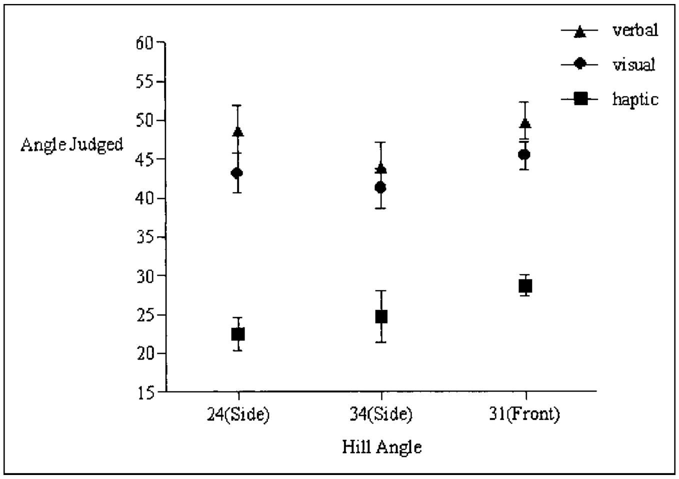

Fig. 3. Mean verbal, visual, and haptic estimations (±1 *SE*) of the hill's slant for the two side views in Experiment 1 and the normative frontal view from Proffitt, Bhalla, Gossweiler, and Midgett (1995).

ings surrounded the hill scene and was visible when the observer turned his or her head.

Apparatus

Participants viewed a computer graphics rendering of the hill environment through a head-mounted display (HMD). This virtual environment was designed and created using Alice 98, a three-dimensional computer graphics authoring software. The execution of the program, rendering, and tracking were handled by a Gateway 2000 computer with a 233-MHz Intel Pentium processor, the Microsoft Windows 95 operating system, 256 MB RAM, and a Diamond Multimedia 3D graphics card.

Observers viewed the virtual environment through a Virtual Research V8 HMD with two active-matrix color LCDs operating in a pseudo-VGA video format. The resolution of each display screen was 640 pixels (horizontal) × 480 pixels (vertical), per color pixel. The field of view per eye was 50° (horizontal) × 38.6° (vertical). This HMD presented a bi-ocular display, meaning that the two display screens presented the same image to each eye, rather than the two different images of a stereoscopic pair. These images were viewed through collimating lenses that allowed the observer's eyes to focus at optical infinity. The screen refreshed at a rate of 60 Hz. The computer registered six degrees of freedom of the position and orientation of the HMD through an Ascension SpacePad magnetic tracker. The computer used this position and orientation information to update the scene appropriately. The end-to-end latency of the VR system, which was calculated with the pendulum method described by Liang, Shaw, and Green (1991), was approximately 100 ms. The end-to-end latency is the length of time it takes the tracking system to sense the HMD position and orientation changes caused by the observer's head movements and then update the scene in the HMD.

Design

Each participant saw all of the hills in random order in either the side ($n = 12$) or front ($n = 12$) condition. All observers reported their judgments on both the verbal and the haptic measures. The order of the measures (verbal or haptic) was counterbalanced across subjects.

Procedure

After placing the HMD on their heads, participants were encouraged to move and look around in the virtual world to become familiar with the immersive VR experience. When they felt comfortable, they were instructed to face the side (or front) of the hill and to give verbal and haptic responses (as described in Experiment 1). Instructions were given before the participants wore the HMD, and were repeated again after they were in the virtual world. The scene became a dark blue color between trials and then reappeared with a hill of a new angle. Participants were allowed to move around while looking at each hill, but then were to face directly either to the side or to the front of the hill while giving their responses.

Results and Discussion

As in Experiment 1, there was no overall difference between viewing the hills from the side compared with the front. Figure 5 shows that observers still greatly overestimated their verbal responses, whereas haptic responses were much more accurate for both side and front views. A 2 (measure) × 12 (hill) × 2 (view) × 2 (sex) × 2 (order of measures) ANOVA was performed with measure and hill as within-subjects variables and view, sex, and order as between-subjects variables. As expected, the analysis indicated an effect of measure, $F(1, 16) = 222.99$, $p < .001$, and hill, $F(11, 176) = 204.94$, $p < .001$. There were no between-subjects effects of view ($p = .75$), sex ($p = .83$), or order ($p = .56$). However, there was a View × Measure interaction, $F(1, 16) = 4.77$, $p < .04$. This interaction revealed that there was no difference between front and side views in the overestimation of slant for the verbal measure ($p = .26$), but the haptic measure showed somewhat greater estimations for views from the side compared with the front, $F(1, 22) = 6.72$, $p < .02$. Despite this difference, Figure 5 illustrates the overall effect of highly overestimated verbal responses and more accurate haptic responses for both view conditions.

Difference scores between the estimations given and the real inclines of the hills were calculated for both the verbal and the haptic measures to assess accuracy. Repeated measures ANOVAs performed on these difference scores indicated that both measures were different from the actual inclines of the hills for the side views, $F(1, 11) = 160.02$, $p < .001$, for the verbal measure and $F(1, 11) = 31.85$, $p < .001$, for the haptic measure. Similarly, both measures were different from the actual inclines for the front views, $F(1, 11) = 51.69$, $p < .001$, for the verbal measure and $F(1, 11) = 134.51$, $p < .001$, for the haptic measure. Verbal judgments were greatly overestimated, and although haptic judgments were much more accurate, they were significantly underestimated. The results replicate the findings in VR presented in our previous study (Proffitt et al., 1995).

GENERAL DISCUSSION

We assessed slant perceptions for hills viewed from the side. We had previously found striking verbal and visual overestimations when hills were viewed head-on (Bhalla & Proffitt, 1999; Creem & Proffitt, 1998; Proffitt et al., 1995), and wanted to assess the generalizability of these findings over different viewpoints. Specifically, we wanted to know whether viewing a hill from the side—a perspective that pro-

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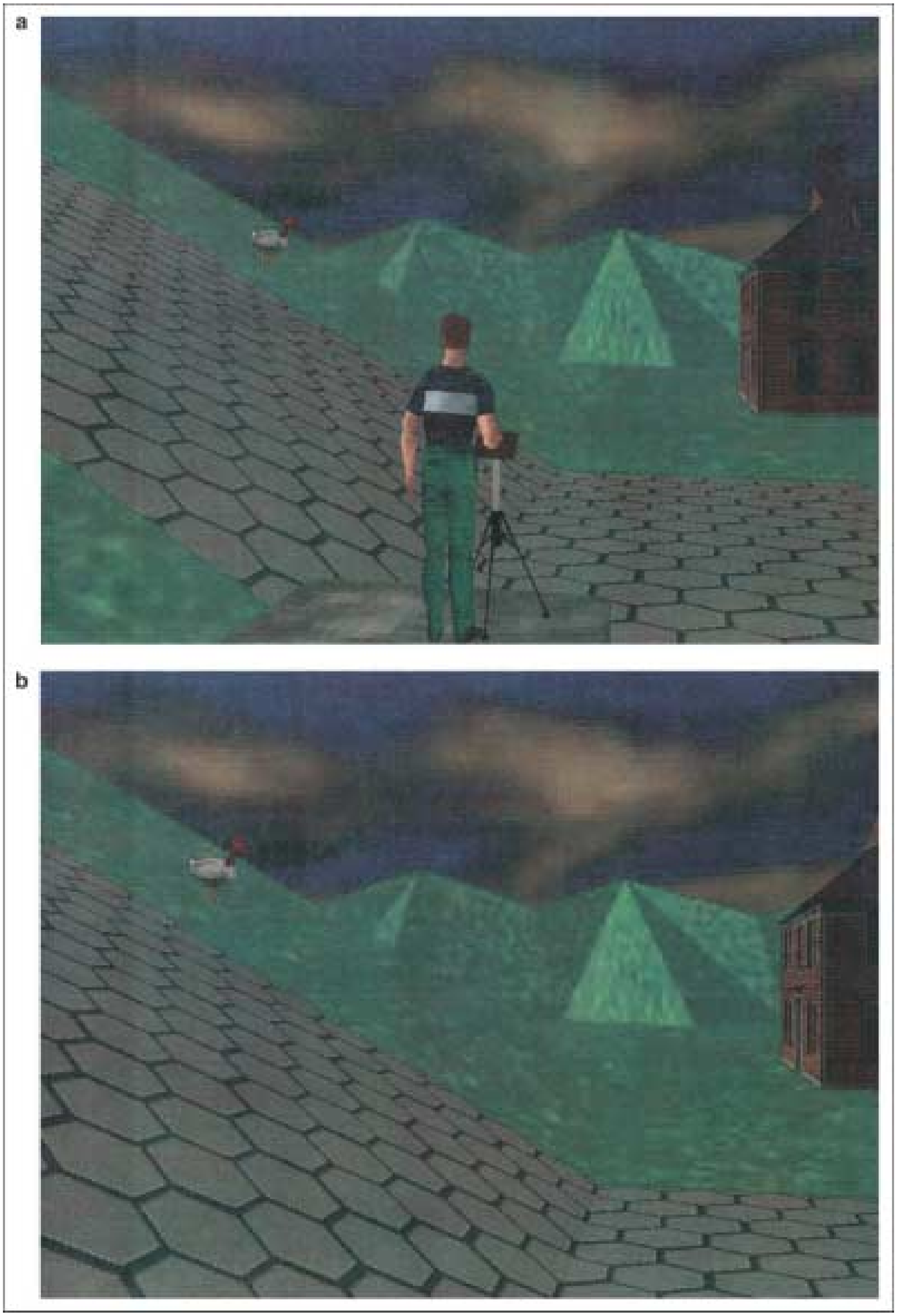

Fig. 4. The virtual cobblestone hill viewed from the side (a) from an outsider's point of view and (b) from the observer's point of view.

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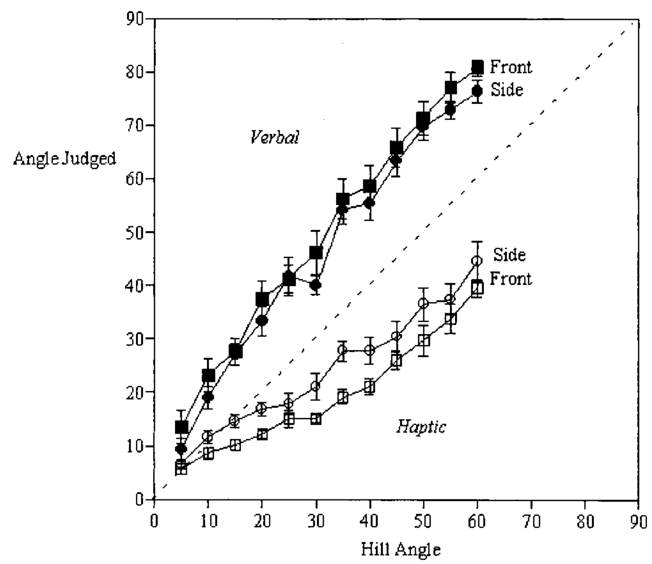

Fig. 5. Mean verbal (filled symbols) and haptic (open symbols) estimations (±1 *SE*) of slant for the 12 hills shown in side and front views in virtual reality in Experiment 2.

vides direct visual specification of angles—would result in more accurate conscious judgments. It did not. Both experiments found large conscious overestimations, and relatively accurate visually guided adjustments.

In Experiment 1, we asked observers to judge the incline of a real hill from two different side views. The views differed in the background information provided and the actual degree of incline. However, there were no significant differences between the estimations of slant for the two side views and the frontal view taken from the normative data of Proffitt et al. (1995). In Experiment 2, 12 different inclines were shown to observers in VR, and they were asked to give verbal and haptic measures while facing the incline or facing its cross-section. Overall, there was no effect of the observers' viewpoint on judgments of slant.

In our earlier articles, we argued that the conscious overestimation of slant is adaptive and reflective of psychophysical response compression (Bhalla & Proffitt, 1999; Proffitt et al., 1995). Psychophysical response compression means that participants' response sensitivity declines with increases in the magnitude of the stimulus. When the judgments are expressed as a power function, the exponent is less than 1. Thought of graphically, the function shows a positive decelerating relationship between the magnitude of the stimulus and that of the response. Response compression is evident in almost all magnitude-estimation contexts. Sensitivity to changes in luminance, for example, declines with the magnitude of the background luminance. Response compression is adaptive because it allows for heightened sensitivity to small energy changes at small ambient energy values. With respect to conscious geographical-slant perception, response compression promotes sensitivity to small changes in slant within the range of small slants that are of behavioral relevance for people. Overestimation necessarily results from a response compression function that is anchored at 0° and 90°. People are accurate at 0°—they can tell whether the ground is going up or down—and for similar reasons of discontinuity they are also accurate at 90°.

The conscious perception of geographical slant relates distal inclines to behavioral potential. Hills appear steeper when one is fatigued, encumbered by a heavy backpack, out of shape, old, or in declining health (Bhalla & Proffitt, 1999). Geographical-slant perceptions are grounded in pragmatic considerations as opposed to strictly geometric criteria. Even though the angles of hills are directly evident when viewed from the side, slant perceptions continue to be grossly overestimated.

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