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Perceiving Virtual Geographical Slant: Action Influences Perception

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In 4 experiments, the authors varied the extent and nature of participant movement in a virtual environment to examine the influence of action on estimates of geographical slant. Previous studies showed that people consciously overestimate hill slant but can still accurately guide an action toward the hill (D. R. Proffitt, M. Bhalla, R. Gossweiler, & J. Midgett, 1995). Related studies suggest that one's potential to act may influence perception of slant and that distinct representations may independently inform perceptual and motoric responses. The authors found that in all conditions, perceptual judgments were overestimated and motoric adjustments were more accurate. The virtual environment allowed manipulation of the effort required to walk up simulated hills. Walking with the effort appropriate to the visual slant led to increased perceptual overestimation of slant compared with active walking with the effort appropriate to level ground, while visually guided actions remained accurate.

The phenomenon that what humans *perceive* is not always consistent with how they *act* suggests that visual space may be represented differently by separable visual systems for specific goals. In circumstances where conscious perception may be biased, actions directed toward a stimulus often remain accurate. For example, to the everyday observer, hills appear to be steeper than their physical slant. However, this bias in visual awareness is not revealed through a visually guided action directed at the hill (Bhalla & Proffitt, 1999; Creem & Proffitt, 1998; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Proffitt, Creem, & Zosh, 2001). Furthermore, manipulations of behavioral potential (e.g., wearing a heavy backpack or going on a long run) have been shown to increase conscious overestimations of slant (Bhalla & Proffitt, 1999; Proffitt et al., 1995) but not visually guided actions. In these studies, visual awareness of slant was assessed by verbal report as well as by visual matching of a pie-shaped segment on a disk. The visually guided action was the adjustment of a palm board (without vision of the hand) to correspond to the slant of the hill. These results involving slant perception, along with recent evidence of the influence of perceived effort on distance perception (Proffitt, Stefanucci, Banton, & Epstein, 2003), suggest that the potential to act in an environment influences phenomenal perception of space. Our experiments addressed the relationship between action and perception by examining how the contribution of biomechanical information gathered from walking on hills influenced participants' judgments of hill slant within a simulated mountainous environment.

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Both real- and virtual-environment studies have demonstrated that perceptual estimates of geographical slant are largely overestimated, whereas haptic estimates are nearly accurate when participants judged hills from a stationary point without actually walking on the hills (Bhalla & Proffitt, 1999; Creem & Proffitt, 1998; Proffitt et al., 1995, 2001). Geographical slant is defined as the angle of a surface with respect to the horizontal ground plane (Gibson & Cornsweet, 1952). The large-scale geographical slant perception findings are consistent with a history of slant perception studies showing that surfaces are perceived to be closer in the frontoparallel plane than indicated by the perspective geometry (e.g., Epstein, 1981; Perrone, 1982; Perrone & Wenderoth, 1991).

One account for the distinction between verbal/visual and haptic responses with respect to hill slant is that two independent visual systems function to transform the same visual information by using different frames of reference for different purposes (Milner & Goodale, 1995). The "what" system works to process the visual stimulus for conscious perception, using multiple frames of reference for longer lasting representations that may later inform actions. A second "how" system works in the immediate time to transform visual information in egocentric coordinates for actions guided toward a specific spatial location. These two systems have been broadly defined, both functionally by the goals that they subserve and anatomically by projections from the primary visual cortex. The "what" or *ventral* stream projects to the inferior temporal cortex, whereas the "how" or *dorsal* stream projects to the posterior parietal cortex.

Other related accounts (Glover & Dixon, 2002; Glover, in press) distinguish between planning, which is susceptible to the influence of context and consciousness, and a time-limited unconscious motor control system. Defined in this way, two different action systems may be subserved by the inferior and superior regions of the parietal lobe, respectively. Previc (1998) also has defined a model based on different action systems by making distinctions between near and far space with respect to body-environment interactions.

A number of studies with neurologically intact humans have demonstrated behavioral dissociations that support accounts of separable visual representations for phenomenal awareness or planning and direct motor control (e.g., Aglioti, DeSouza, & Goodale, 1995; Bridgeman & Huemer, 1998; Bridgeman, Kirch, & Sperling, 1981; Burr, Morrone, & Ross, 2001; Glover, 2002; Haffenden & Goodale, 1998; Jackson & Shaw, 2000). In contrast, others have suggested, specifically with the use of visual illusions, that a single representation informs both conscious perception and visuomotor control (Franz, 2001; Franz, Fahle, Bulthoff, & Gegenfurtner, 2001; Franz, Gegenfurtner, Bulthoff, & Fahle, 2000). These results can be interpreted in multiple ways (see Carey, 2001). Franz et al. (2000, 2001) suggested that the apparent association negates the existence of separate "what" and "how" visual systems. An alternative explanation is that the systems are only "nearly separable" and that the dorsal stream operates independently only in limited circumstances. Research has demonstrated that the dorsal stream may remain independent only when actions recruit egocentric coordinate systems that are directed toward real objects and are performed in real time, without delays (Creem & Proffitt, 1998; Hu, Eagleson, & Goodale, 1999; Hu & Goodale, 2000). Creem & Proffitt (2001a) have suggested that the demonstrated interactions do not negate evidence for separable systems; rather, they exemplify how multiple visual systems work together to allow an organism to function adaptively as a whole.

Although there is growing evidence for interactions between these systems, we might intuitively predict the findings of Bhalla and Proffitt's (1999) series of experiments indicating separate representations for the perception and action measures of slant. They found that manipulations of one's behavioral potential influenced perceptual reports of hill slant but visually guided motor responses remained consistent with the visual information provided. Proffitt and colleagues (Bhalla & Proffitt, 1999; Proffitt et al., 1995) have argued that conscious overestimation of slant is adaptive. A human's perception of walkable slopes is influenced by their perceived effort of traversing that slope. This conscious, pragmatic representation may influence choice of gait or speed as well as the decision of whether to traverse the hill at all. However, an independent visuomotor system should transform the visual properties of the distal hill accurately for immediate action. Creem and Proffitt (1998) demonstrated both dissociation and interaction with geographical slant by implementing different temporal delays between viewing and responding to hill slant. They found that when hills were remembered, the hills were reported to be steeper than when they were perceived. However, the differential time delay influenced whether visuomotor judgments remained independent from conscious memorial judgments. After a short time delay, in the presence of the hill, motor adjustments of a tilting board with the participant's hand remained accurate. After a longer delay of one day, when judgments were made from memory without the visual hill present, motor responses increased proportionately to the perceptual response. These findings were similar to studies using illusory displays (e.g., Bridgeman, Peery, & Anand, 1997) that found an association between perceptual and motoric responses when delays were implemented. Creem and Proffitt (1998) suggested that without a direct visual stimulus to inform action, the visuomotor system relies on information from a conscious perceptual system. These claims have been supported by other recent studies that have investigated the factors that influence an interaction between the two visual systems (Bridgeman et al., 1997; Creem & Proffitt, 2001b; Haffenden & Goodale, 2000; Hu et al., 1999).

Much of the research examining separable and interactive systems for perceptual awareness and visuomotor control has studied how conscious perception influences action. The present experiments investigated the contribution of acting on hills to both perceptual and motoric judgments of hill slant. We asked whether biomechanical information resulting from walking on hills would influence judgments of slant. We predicted that the information gained from effortful walking would lead to an increase in conscious overestimation of slant. Despite this predicted overt change in hill slant estimation, we would expect a motorically based estimation to remain accurate if it could be guided independently by the presence of the virtual hill.

We used a semi-immersive locomotion interface, the Treadport (Sarcos, Salt Lake City, UT), which allowed us to decouple biomechanical and visual information about slant. The Treadport consists of a large treadmill surrounded by three projection screens. In all conditions, participants were attached to a mechanical tether that tracked their position on the treadmill, allowing them to control their own walking pace with the speed of the treadmill belt adjusting as necessary. The tether is capable of applying a force to the participant that simulates the added efforts involved in walking up a slanted surface and in changing translational velocity (Hollerbach et al., 2001). In four experiments, we varied the extent to which the participant experienced self-movement information. In Experiment 1, no translational movement over the hill was allowed. Experiment 2 visually translated the participant over each hill by updating his or her station point. Participants did not use any biomechanics to change their viewing position. In Experiment 3, the participants were allowed to physically walk up each hill, but they experienced forces corresponding to walking on a flat terrain. Experiment 4 replicated the walking method of Experiment 3, but participants experienced forces that systematically increased with increasing hill slant. Walking with forces appropriate to the visual hill slant led to increased overestimation in phenomenal awareness compared with visual movement or active walking without forces. Haptic estimates did not differ across conditions.

General Method and Materials

Participants

Sixty-four psychology students (16 in each experiment, 33 male and 31 female) participated for course credit. Each had normal or corrected-to-normal vision and no locomotion impairments. The experimental procedures were approved by the University of Utah Institutional Review Board, and all participants gave their informed consent before beginning the study.

Apparatus and Stimuli

The Treadport (see Figure 1) has a 6×10 ft (1.83×3.05 m) belt surface. The tether mechanism applies force to the participant via a torso harness worn by the participant (Hollerbach et al., 2001; Hollerbach, Xu, Christensen, & Jacobsen, 2000). This force allows simulation of two aspects of locomotion that do not occur in normal treadmill walking: the inertial effects associated with changes in walking speed and the changes in effort associated with walking up or down hills. The speed of the motorized belt is controlled by the speed of the moving participant. The Treadport is surrounded by three 6×8 ft (1.83×2.44 m) rear projection

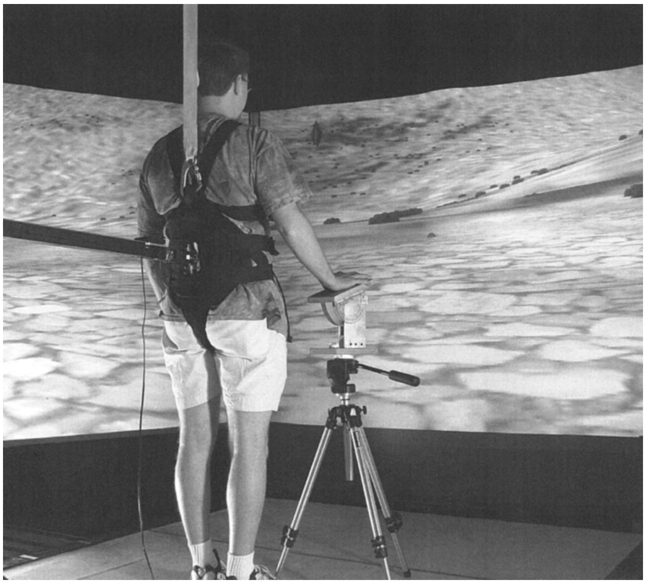

Figure 1. A participant standing on the Treadport using the palm board.

screens that span approximately a 180° horizontal field of view. Participants stood in the center of the belt and viewed a computer-generated environment presented on the three continuous screens. Because the treadmill itself is fixed in place, physically correct rotations are not possible. Instead, it is necessary to simulate rotations in the virtual world while limiting rotational movement in the physical world. For the experiments described below, virtual world rotations occurred only when participants were not translating. Participants signaled an intention to rotate their viewpoint in the virtual world by twisting their torsos in the desired direction. Viewpoint rotation occurred until participants recentered their torsos in the forward direction.

The environment was a simulation of a 2 × 2 km portion of the Wasatch mountains outside of Salt Lake City, Utah, based on United States Geological Survey data. The terrain geometry had a 30-m elevation resolution, with a 1-m texture resolution based on an orthonormal photograph that was segmented and colorized (Premoze, Thompson, & Shirley, 1999). Close to the viewpoint, the 1-m resolution ground texture was augmented with a higher resolution detail texture picturing the rocky surface typical of the actual terrain. The computer-generated environment was rendered by an Onyx2 R12000 (SGI, Mountain View, CA), with two IR2 rendering pipelines. The environment ran at no less than 22 frames per second.

Ten hill sites were selected on the basis of the degree and uniformity of their slopes. The hill slants were 4.26°, 5.39°, 6.85°, 7.83°, 9.65°, 11.91°, 13.13°, 14.93°, 16.80°, and 23.49°. Two additional hills (5.71° and 9.46°) were presented as practice trials. Hemispherical markers were placed on the terrain to designate the hill that the participant was asked to judge. These markers were randomly sized and randomly colored (one of six dark colors distinct from the terrain coloring). For the first practice trial, we placed 60 of these markers on the terrain to the left of the starting point so that the participant could see the range of sizes and colors. It was our intention to minimize the possibility that the hill marker's size would be used as a distance or size cue. The spheres were placed so that when the viewer was making judgments on the hill, the hill marker was about 14° below the viewer's horizon line so that for any given hill, the marker appeared in the same location in screen space. Thus, the distance between the participant and the marker varied (3.2 m to 8 m) on the basis of the slope, but as the judgments were made, the marker always subtended the same visual angle and was positioned in the same place in the image plane.

Procedure

In all experiments, participants were acquainted with the Treadport and instructed how to adjust the harness and how to turn while standing in place. Participants stood on each hill, facing a marker (see Figure 2), and gave three types of judgments of the slope of the hill at the marker: verbal, visual, and haptic, with the order counterbalanced across participants. For the verbal estimate, participants were instructed to report a number in degrees that reflected the slope of the hill. A description of 0° (as flat ground) and 90° (as a vertical wall) was provided by the experimenter to each participant so that it could assumed that all participants began with a similar basic knowledge of angles. For the visual measure, they adjusted a *pie slice* on a handheld disk to make the perceived cross section of the hill while holding it in the frontal plane (see Figure 3). For the haptic estimate, participants placed the palms of their dominant hands on a tilting board that was sitting on top of a tripod placed about waist high (see Figure 1). They were instructed to tilt the board backward to match the slope of the hill without looking at the palm board or their dominant hands as if they were placing their hands on the hill. We have previously defined the haptic adjustment as one that recruits the visuomotor system because it involves an egocentric adjustment of one's hand to become parallel to the slant of the hill. In contrast, the verbal and visual measures require knowledge of the environmental horizontal to represent geographical slant (Creem & Proffitt, 1998). In all experiments, participants were encouraged to rotate their viewpoint so that they could examine the regions surrounding the hill at which they were looking. The rotational viewing allowed the participant to see the entire space surrounding the hill, including the regions behind them. Our intent was that the context would provide a better sense of presence in the virtual environment. In addition to this rotational move-

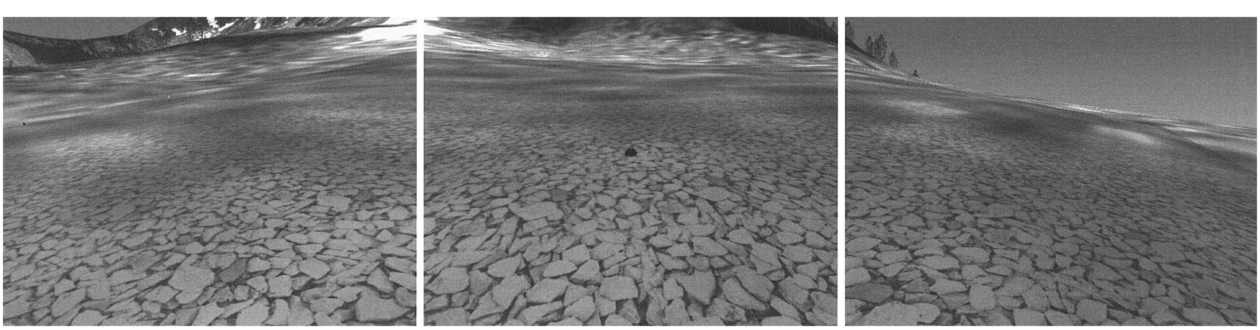

Figure 2. The participant's view of the target on the 9.65° hill as presented on the left, center, and right screens of the Treadport.

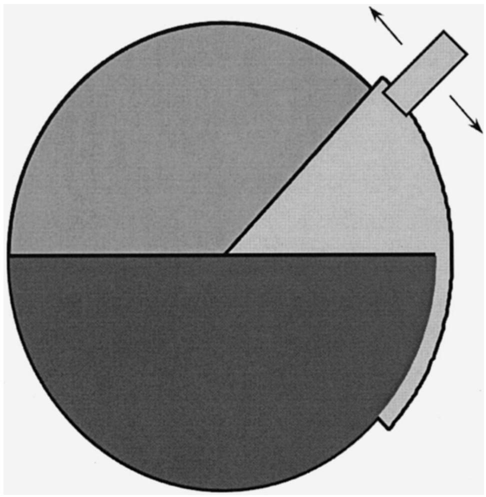

Figure 3. The visual disc.

ment, the amount of translational movement over the hill varied in each experiment. After giving three judgments, the participant was transported to a new hill site. Each hill site was repeated twice. Hills were presented in a different random order for each participant. The entire experiment was completed in about 1 h. The same visual display and response measures were used in all four experiments; the only difference was the extent and manner of locomotion experience.

Analyses

A 3 (measure) × 10 (hill) analysis of variance (ANOVA) was performed on mean responses for Experiments 1, 2, and 3, with measure and hill as within-subjects variables. A 3 (measure) × 7 (hill) ANOVA was performed for Experiment 4. Between-experiment analyses were also performed and are described in subsequent sections.

Experiment 1: Stand at Hills

Our first experiment aimed to establish baseline performance of geographical slant perception on the Treadport without locomotion experience. We presented a visual environment in which participants could rotate their bodies to look to the side and behind themselves, but they experienced no translational flow information with respect to the virtual environment.

Method

Participants were transported visually to each hill site and were given no additional movement experience other than rotation while standing in place. They responded to each hill with three measures as described above.

Results and Discussion

Similar to previous findings of geographical slant perception, we found verbal and visual overestimation of hill slant, but nearly accurate haptic estimates (see Figure 4). The ANOVA indicated main effects of hill measure, $F(2, 30) = 52.92$, $p < .01$; of hill, $F(9, 135) = 89.80$, $p < .01$; and a Measure × Hill interaction, $F(18, 270) = 18.76$, $p < .01$. Planned simple contrasts revealed that both the verbal and visual measures were significantly greater than the haptic measure ($p < .01$). As in previous findings (e.g., Creem & Proffitt, 1998; Proffitt et al., 1995), the data were fit well by both linear and power functions ($R^2 \geq .90$, for both linear and power functions for all measures). Unlike the previous studies' finding of a compression function associated with highest sensitivity within walkable hill range, the exponent of the power function was greater than 1 for all measures, indicating an increase in estimates with increasing hill degree (verbal, $y = 1.01x^{1.31}$; visual, $y = 2.18x^{1.02}$; haptic, $y = 0.81x^{1.09}$. However, this distinction was likely a result of our range of hills. Proffitt and colleagues presented hill angles that ranged from 2° to 60°, whereas our hills were all within potentially walkable angles (maximum of 24°). It follows that participants would show maximum sensitivity to steep hills that approach the limits of affording action. Notably, there was an apparent increase in overestimation as a function of hill angle from 12° to 13°. We speculate that some of the variability in the responses was due to variation in lighting and context in the rendered graphics. This is difficult to precisely control for because environmental variability is an important factor in visual realism.

In all, the results from the first experiment replicated the dissociation between phenomenal awareness and visually guided action in a virtual mountainous environment. All previous slant studies using this methodology (Bhalla & Proffitt, 1999; Proffitt et al., 1995, 2001) focused on grassy or paved slopes found in a university setting (or created in a similar cartoon-like virtual setting). We have shown the same effects in a simulated mountain range based on United States Geological Survey data. Furthermore, this experiment validates the use of the Treadport for studies of large-scale slant perception. In Experiment 2, we assessed the influence of perceived locomotion on the participants' judgments by allowing them to "move" (visual translation without physical locomotion) through the environment. It is possible that the suggestion of walking on hills could lead to a greater potential for acting on the

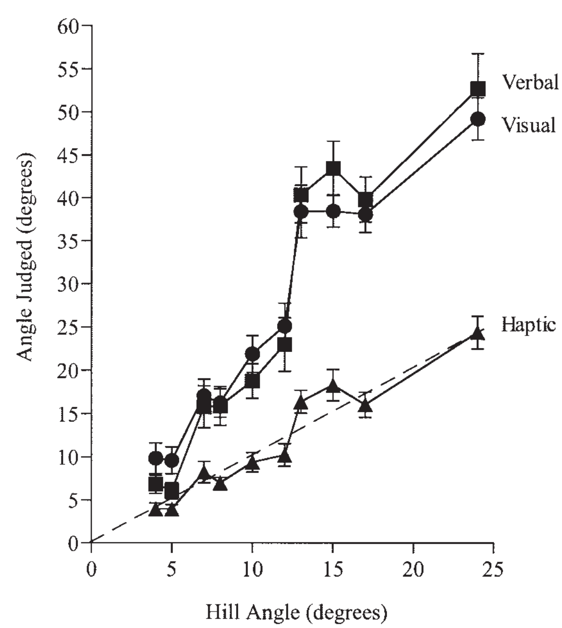

Figure 4. Verbal, visual, and haptic judgments (±1 *SE*) as a function of hill angle in Experiment 1. The dotted line represents accurate performance.

hills and an increase in conscious overestimation. However, we predicted that the passive, nonmotoric nature of the movement over hills would lead to little change in judgments compared with Experiment 1.

Experiment 2: Visual Translation

Method

Participants were transported visually to each hill site. They stood 25 to 30 m away from the position where they had viewed the hill in Experiment 1. They were told to signal the experimenter when they were ready, and they would "move" up the hill (1 m/sec) until they reached the marker (which was in the same position as in Experiment 1). The sense of movement was created by translating the visual world; the participant remained stationary, standing on a stationary treadmill belt. The participant's viewpoint was moved in the direction of the target while maintaining a constant eyeheight above the ground. The target always remained centered on the center Treadport screen. Participants translated to the marker for a total distance of approximately 33 m on each trial. After reaching the marker, they were transported back to a location on the hill (the same location as in Experiment 1) and then made three judgments about the slant of the hill. The participant was encouraged to rotate his or her torso to look around, as in Experiment 1, before making the judgments.

Results and Discussion

In all, visual translation through the world did not change slant estimates for any of the measures. Slant judgments after visual translation replicated those seen in Experiment 1 (see Figure 5). The ANOVA revealed effects of measure, $F(2, 30) = 118.74$, $p < .01$; of hill, $F(9, 135) = 98.10$, $p < .01$; and a Measure × Hill interaction, $F(18, 270) = 30.26$, $p < .01$. Planned simple contrasts indicated that both the verbal and visual responses were greater than the haptic estimates ($p < .01$). As in Experiment 1, both linear and power functions fit the data well ($R^2 \geq .91$, for both linear and power functions for all measures). As in Experiment 1, the exponents for the power functions were slightly less than or greater than 1, suggesting little compression (verbal, $y = 1.75x^{1.109}$; visual, $y = 2.90x^{.91}$; haptic, $y = 1.16x^{.95}$).

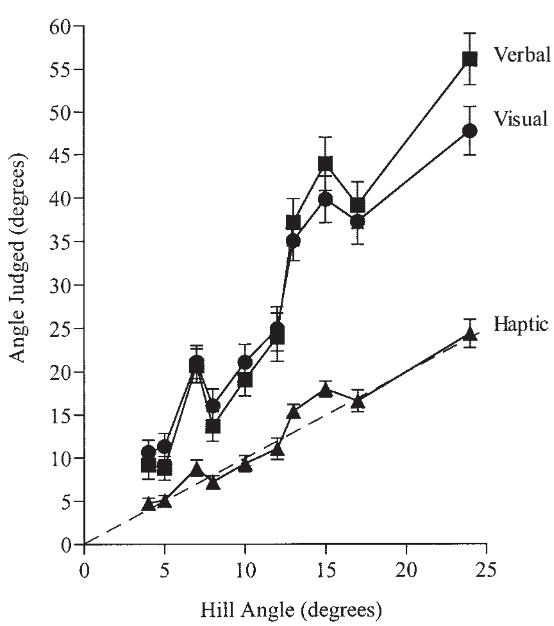

Figure 5. Verbal, visual, and haptic judgments (±1 *SE*) as a function of hill angle in Experiment 2. The dotted line represents accurate performance.

There was little difference between the judgments given in Experiments 1 and 2. It was important to establish this finding for two reasons. First, it is possible that merely the suggestion of traversal on hills could lead to changes in conscious overestimation. Second, it was important to establish baseline data that involved visual translation without body movement to compare to active walking conditions in Experiments 3 and 4. Experiments 3 and 4 investigated the influence of active walking on slant perception.

Experiment 3: Walk Without Slope Forces

In Experiments 3 and 4, we took advantage of the Treadport's unique ability to allow active walking and, at the same time, to manipulate the forces applied to the participant using the Treadport's tether. The Treadport, unlike other virtual environments that use head mounted displays or desktop displays, allows a participant to actively locomote through large-scale space. Our goal was to assess the effects of the effort of walking on hills on estimations of slant. We explored two aspects of effortful walking: one involving only the effort associated with locomotion over level ground (Experiment 3) and the other involving the increased effort of walking up hills (Experiment 4).

Bhalla and Proffitt's (1999) slant studies showed that participants with decreased physiological potential gave greater conscious overestimations of slant, suggesting that hill slant is perceived with respect to potential interaction. They found that hills were perceived as steeper when participants were encumbered by wearing a heavy backpack, when they were fatigued after a long run, when they were of low physical fitness, or when they were elderly or in poor health. Despite this increase in conscious overestimation, their visually guided actions, as reflected through the haptic response on the palm board, remained accurate. We predicted that the additional cues resulting from the actual experience of effortful walking would lead to greater conscious overestimations of hill slant. On the basis of an assumption of separable visual systems for awareness and visuomotor control, we predicted that the haptic estimate would reflect an independent visuomotor system informed directly by the visual hill and would remain accurate.

Experiment 3 questioned whether active walking alone, without changes in effort corresponding to the visual hill slant, would lead to increased overestimation. Participants walked to the target on the hill while the Treadport applied only the inertial forces associated with change in walking speed. No forces simulating walking up a slanted hill were applied.

Method

Before beginning the study, participants were given 3 min of practice walking with slope forces appropriate to level ground in a region of the environment different from the testing region to become comfortable with walking on the Treadport. They were then taken off the Treadport and instructed to walk in the hallway of the building for 3 min before returning to stand on the Treadport. This procedure attempted to account for any tendency for the participant to adapt to a distinct mapping of optic flow and treadmill walking, which was found in recent studies (Rieser, Pick, Ashmead, & Garing, 1995). After returning to the Treadport, participants were transported visually to each site and placed at the same distance from the bottom of the hill as in Experiments 1 and 2. They were instructed to walk in a straight path to the marker on the hill. The ability to turn while walking was disabled, so that their straight path would more closely resemble the visual movement in Experiment 2. Only forces simulating inertial effects associated with changes in walking speed were applied. After stopping at the marker, participants were visually transported to a position on the hill (to the same location as in Experiments 1 and 2). They were encouraged to look to the sides before making their three judgments.

Results and Discussion

Active walking without slope forces led to overestimation in verbal and visual judgments but to accurate haptic estimations, similar to the findings in Experiments 1 and 2 (see Figure 6). The ANOVA revealed main effects of measure, $F(2, 30) = 70.70$, $p < .01$; of hill, $F(9, 135) = 108.84$, $p < .01$; and a Measure × Hill interaction, $F(18, 270) = 25.70$, $p < .01$. Planned simple contrasts indicated that the visual and verbal measures differed from the haptic estimate ($p < .01$). As in the previous experiments, both linear and power functions fit the data well ($R^2 \geq .91$, for both linear and power functions for all measures). Exponents for the power functions were close to or greater than 1 for all measures, indicating the lack of compression seen in the other conditions (verbal, $y = 1.31x^{1.25}$; visual, $y = 3.05x^{.908}$; haptic, $y = 1.29x^{.944}$).

The estimations given after active walking in Experiment 3 did not differ from those given after visual translation in Experiment 2. We conducted mixed between- and within-subject 2 (movement condition) × 10 (hill) ANOVAs to compare the two experiments for each measure. There were no significant effects of experiment for any of the measures (verbal, $p = .40$; visual, $p = .66$; and haptic, $p = .55$) and no Experiment × Hill interactions ($p > .10$, for all measures). Although participants' estimations followed the normative pattern of results seen in the first two experiments as well as previous real-world studies, there was no increase in overestimation as a result of active walking. Experiment 4 examined the influence of systematic variation of effort corresponding to hill slant on overestimation of slant.

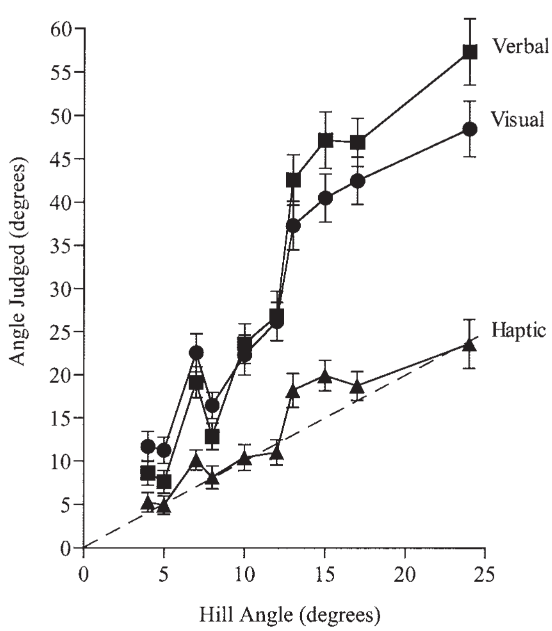

Figure 6. Verbal, visual, and haptic judgments (±1 *SE*) as a function of hill angle in Experiment 3. The dotted line represents accurate performance.

Experiment 4: Walk With Slope Forces

Experiment 3 demonstrated that active walking on hills with the simulated forces of a flat terrain did not increase the standard overestimation seen in the earlier experiments. Although walking involved additional effort and active interaction with the virtual environment, estimations did not change. Our final experiment used the Treadport's ability to simulate forces corresponding to uphill walking to assess the influence of increased effortful walking on slant estimates. We predicted a change in verbal and visual estimates but that haptic estimates would remain accurate.

Method

Stimuli. Seven out of the 10 hills from Experiments 1 to 3 were used in the present experiment. The 3 steepest hills (15°, 17°, and 24°) were removed because the forces applied by the Treadport made it too difficult for participants to begin walking at these higher degree hills.

Procedure. The procedure was the same as in Experiment 3 except that systematic forces corresponding to actual hill slant were applied as the participants walked on the hill to the target. These forces were based on previous measures of subjective reports involving matching tether force with walking on a physically slanted treadmill and on biomechanical comparisons between tether and slope walking (Hollerbach et al., 2001). The additional forces simulating inertial effects associated with changes in walking speed were also applied. Hollerbach et al. (2001) demonstrated that the simulation of slope forces with the Treadport tether led to postural and biomechanical adjustments similar to walking on real slopes. Thus, posture did vary as a function of the presence of slope forces while walking in Experiments 3 and 4. However, the slant judgments were made after the walking phase, so that the participants' postures during their verbal, visual, and haptic judgments did not systematically vary between Experiments 3 and 4.

Results and Discussion

Slant judgments made after walking with systematic forces on the hills replicated the pattern seen in the first three experiments. We found a large overestimation in verbal and visual judgments but nearly accurate haptic estimations (see Figure 7). The ANOVA for Experiment 4 revealed main effects of measure, $F(2, 30) = 45.61$, $p < .01$; and of hill, $F(6, 90) = 83.3$, $p < .01$; and a Measure × Hill interaction, $F(12, 180) = 19.48$, $p < .01$. Planned simple contrasts indicated that the visual and verbal measures differed from the haptic estimate ($p < .01$). As in the previous experiments, linear and power functions conformed well to the data ($R^2 \geq .97$, for both linear and power functions for all measures). The exponents for the power functions were greater than 1, indicating a lack of compression (verbal, $y = 1.36x^{1.35}$; visual, $y = 2.02x^{1.15}$; haptic, $y = .71x^{1.25}$).

Notably, the verbal and visual estimates were greater than those seen in the walking-without-forces condition of Experiment 3, but

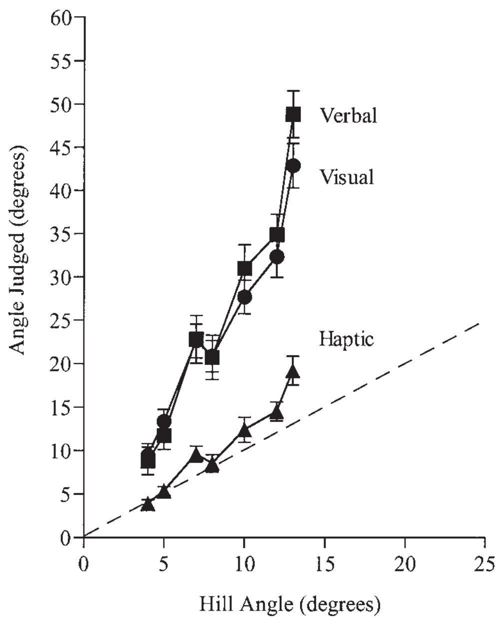

Figure 7. Verbal, visual, and haptic judgments (±1 *SE*) as a function of hill angle in Experiment 4. The dotted line represents accurate performance.

the haptic estimations did not differ. A direct comparison between verbal, visual, and haptic measures on the seven hills included in Experiments 3 and 4 was performed to assess the effect of experienced forces, controlling for active walking, on hill estimates. A mixed within- and between-subject 7 (hill) × 2 (effort) ANOVA was performed for each of the three measures (verbal, visual, and haptic). As Figure 8 shows, verbal responses were greater after walking with slope forces compared with walking without slope forces. There was a main effect of effort (mean difference = 5.36°), $F(1, 30) = 5.663$, $p < .05$, and no Hill × Effort interaction ($p = .22$). The mean percent increase in overestimation in the verbal response from Experiments 3 to 4 was 30.38%.[1] For the visual measure, although there was a trend of an increase in overestimation with slope forces (mean difference = 3.30°, mean percent increase in overestimation = 14.08%), the main effect of effort across all seven hills did not reach significance ($p = .14$). However, a significant Hill × Effort interaction, $F(6, 180) = 2.35$, $p < .05$, was found, and the means indicated an increase in estimates when walking with forces for the four largest hills. To further assess this effect, we performed a subsequent 2 (effort) × 4 (hill) ANOVA on the visual estimates for the four largest hills (8°, 10°, 12°, and 13°), and a significant effect of effort, $F(1, 30) = 4.20$, $p < .05$, was found, with no Hill × Effort interaction ($p = .93$). Finally, for the haptic measure, there was no effect of effort (mean difference = .77°, mean percent overestimation = 5.66%, $p = .59$). To assess the overall difference between the effect of effort on verbal and haptic responses in Experiments 3 and 4, we performed a 2 (effort) × 2 (measure: verbal or haptic) mixed ANOVA, with effort as a between-subjects variable and measure as a within-subjects variable, on the ratio of estimated slant to actual slant. The results confirmed that there was an overall difference between verbal and haptic responses, $F(1, 30) = 98.32$, $p < .01$, and also a Response × Effort interaction, $F(1, 30) = 4.08$, $p = .05$, indicating that the increase in overestimation between Experiments 3 and 4 was significant for the verbal response but not for the haptic response. A 2 (effort) × 2 (measure) ANOVA comparing visual and haptic measures again showed the large effect of measure, $F(1, 30) = 138.87$, $p < .05$, but the Effort × Measure interaction did not reach significance ($p = .29$). In all, the comparison of Experiments 3 and 4 indicates an increase in phenomenal overestimation of slant after walking with forces appropriate to hill slant compared with walking with forces associated with flat terrain. These results suggest that the increased effort of walking in Experiment 4 modified participants' judgments of slant with respect to their ability to traverse the terrain. That the effort manipulation affected the visual measure for only the four steepest hills is a finding in need of further investigation.

We found it necessary to exclude the three steepest slants used in Experiment 3 from Experiment 4 because of the difficulty that participants had walking on the Treadport with the forces associated with those slants. It is possible that the smaller range of slants in Experiment 4 could have contributed to different relative judgments of slant, leading to greater overestimation. In all experiments, participants were instructed to judge each hill independently, without regard to their previous estimations. However, it is difficult to eliminate the possibility of relative scaling when participants are presented with multiple trials. To reduce the contribution of relative judgments to the overall effect, we presented a random order of hills to each participant so that the context of previous and subsequent hills varied across participants and experiments. In addition, to address the possibility that the context of the other hills had a significant effect, we performed a post hoc analysis. We compared the mean estimates given in all of the trials in Experiment 3 that were performed before participants saw the first of the three steepest hills to those that were performed after participants saw the first of the steepest hills (the means excluded the three steepest hills). There was no difference between the means in these two groups ($p > .05$, for all three measures). In all, this additional analysis led us to conclude that trial order did not have a significant effect and reduced the possibility that the increase in overestimation seen in Experiment 4 was a function of relative scaling.

General Discussion

Gibson's (1979) theory of affordances suggests that space and objects are perceived with respect to their potential for action. A locomotion interface and virtual environment allowed us to examine the influence of both biomechanical and visual information on perception of geographical slant. Four studies demonstrated a large verbal and visual overestimation but nearly accurate haptic responses for perception of slant in a simulated mountainous setting, replicating findings seen in real and virtual urban settings. Judgments given after active, effortful locomotion increased for visual awareness but not motoric responses. The results have implications for (a) the influence of pragmatic action-based representations on

[1] Percent increase in overestimation from walking without slope forces to walking with slope forces was calculated for each hill as (Experiment 4 mean − Experiment 3 mean)/Experiment 3 mean.

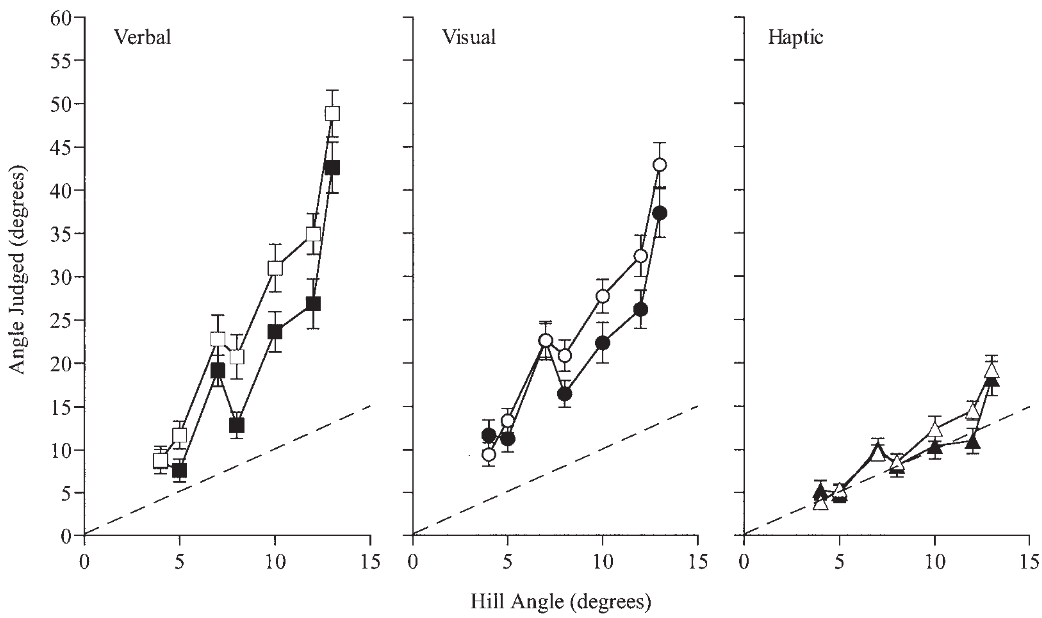

Figure 8. Verbal, visual, and haptic judgments with (open symbols) and without (closed symbols) appropriate slope forces (±1 *SE*) in Experiments 3 and 4. The dotted lines represent accurate performance.

perception, (b) the nature of separable visual systems for perception and action, and (c) the use of large-scale simulated environments for studies of space perception.

Action Influences Perception

Bhalla and Proffitt (1999) demonstrated that changes in physiological potential, or the potential to climb, influenced awareness of hill slant. This was reflected not only in purposeful manipulations of heavy encumbrance or fatigue but also in the differences in behavioral potential associated with physical fitness, old age, and declining health. The present studies extended this finding to overt action; the experienced effort of climbing influenced perceptual awareness of slant. These findings are quite striking, especially in a comparison of Experiments 3 and 4, in which the exact same visual environment and walking procedure was implemented, varying only the extent of forces that were experienced while walking.

These findings support the notion that visual perception is influenced by action-relevant representations. With respect to geographical slant, not only is the slant specified by the visual information provided (e.g., texture gradient, motion parallax) but also by the participant's potential to interact with the visual world. One's potential to climb a hill, or one's experience with climbing a hill, influences one's awareness of the steepness of that hill. The effect of effortful walking supports the claim of Proffitt et al. (1995) that what appears to be a large bias or error in slant perception has an important adaptive function. A hill that is judged to be larger than it is serves to inform planning of gait, energy expenditure, and ultimately, whether to traverse the hill at all.

The influence of both physiological potential and experienced effort on perception was recently investigated by Proffitt et al. (2003) with respect to perceiving distance. In three experiments, they demonstrated that perception of distance can be influenced by both distal extent as well as one's potential to perform an action. Similar to the backpack manipulation with slant perception, their first experiment found that wearing a backpack increased the magnitude of verbal distance estimations. Their second and third experiments involved treadmill walking and a recalibration of walking effort and optic flow. Participants walked on a treadmill while viewing a virtual environment with appropriate optic flow, or with no optic flow (a stationary image). After walking on the treadmill, participants made distance estimations in the real world. Those who had walked while viewing no optic flow estimated that distances were farther than those who had received appropriate optic flow. Proffitt et al. interpreted these results as a change in the calibration between optic flow and effort. Since the effort of walking produced no change in optic flow on the treadmill, an increase in walking effort is needed to walk a certain distance. Thus, they suggested that the change in the effort-optic flow relationship influenced perceived egocentric distance.

In our present studies, we found an influence of effortful walking on perception of slant. However, a question exists as to whether the specific biomechanical cues to uphill walking influenced slant judgments or whether overestimation increased as a function of an overall increase in effort and energy expenditure. In addition, our results suggest that participants combine both biomechanical and visual information in estimating slant. Given the same visual information, participants changed their estimations when slope forces were experienced. In order to further examine the weighting of biomechanical and visual information for slant, we have planned future studies to measure perceptual and motoric slant estimations that rely on biomechanical information alone.

Broadly, a theory of perception informed by action can be supported not only in space perception but in multiple domains of visual cognition. For example, Tucker and Ellis (1998, 2001) suggested that objects "potentiate" actions even when the goal of a task is not to directly interact with the object. In one study, they demonstrated a variation of the Simon (1969) effect, finding that the position of visual objects' handles had a significant effect on the speed of key-press responses, even though the handle position was irrelevant to the task (which was deciding whether the object was upright or inverted). For example, handle orientation toward the right facilitated the key-press response made with the right hand. The premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987) provides one account of the Simon effect, suggesting that motor programs are formed when attention is covertly shifted to a stimulus. The result that viewing an object in a certain position affected potential for subsequent action, suggests that action-related information about objects is represented automatically when an object is viewed. Research from monkey neurophysiology and functional neuroimaging also lends support to this claim (Chao, Haxby, & Martin, 1999; Chao & Martin, 2000; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Grezes & Decety, 2002).

Separable but Interactive Visual Systems

Despite a significant increase in phenomenal awareness of hill slant in Experiment 4, walking with forces, the haptic measure remained unchanged. This dissociation suggests that the motoric response could be directly informed by the visual information provided. These results support a theory of separable visual systems in which visual-spatial information is transformed differently for different purposes. Whereas conscious perception of space may be influenced by one's experience with action, a visually guided response remains influenced by the visual information specified in the environment. These two types of perceptual responses can be broadly placed into anatomically separable visual processing streams projecting from the primary visual cortex. One stream projects ventrally to inferior regions of the temporal lobe, whereas the other stream projects dorsally to the superior parietal lobe. Tasks such as object discrimination and recognition have been attributed to the ventral stream, and egocentric visually guided actions (even those that have object-based goals) such as reaching, pointing, and grasping are associated with the dorsal stream. An alternate model of separable systems could distinguish between the phenomenal representation of hills as a conscious planning system subserved by inferior parietal regions and the direct motoric response subserved by the superior parietal lobule's motor control system (Glover, in press).

Importantly, studies of space perception have also demonstrated that visually guided actions and visual awareness can be informed by the same perceptual variables, related by a transformation or scaling factor. For example, in studies of perception of distance, Philbeck and Loomis (1997) demonstrated that both verbal reports and walking without vision were influenced by a common internal variable of perceived distance. Previous studies with geographical slant also demonstrated this calibration between perceptual and motoric responses, with the finding that visually guided actions may be either directly influenced by a visual stimulus or indirectly influenced by a cognitive representation. Bhalla and Proffitt (1999) and Proffitt et al. (1995) showed a measure of internal consistency between the awareness of slant and the action performed. For example, a person looking at a 10° hill will verbally report that it is about 30°, but they will set the palm board to 10°. Given the verbal instruction to set the palm board to 30°, they will set it to 10°. This internal consistency suggests a calibration between an explicit awareness of what one believes to be 30° (either an explicit instruction or the direct perception of the hill) and a motoric adjustment of 10°. Consistent with this reasoning, Creem and Proffitt's (1998) memory-for-slant studies demonstrated that without a visual hill present, the motoric adjustment was indirectly influenced by a stored representation of the hill.

Research within the past 10 years has demonstrated both independence and interaction in the functionally defined "what" and "how" streams. Studies have demonstrated that the dorsal stream operates independently when using egocentric coordinate systems and when processing visual information for action without time delays. Interactions have been found when delays are introduced between the visual presentation of a stimulus and an action (Bridgeman et al., 1997; Creem & Proffitt, 1998; Hu, Eagleson, & Goodale, 1999), when binocular cues are restricted (Marotta, DeSouza, Haffenden, & Goodale, 1998), when actions depend on learned perceptual associations (Haffenden & Goodale, 2000, 2002), and when semantic information is tied to the object to be grasped (Creem & Proffitt, 2001b). All of these examples demonstrate that visual systems that can be defined as separable also interact in functionally adaptive ways in the normal individual. Our studies demonstrate independence between awareness of slant and visually guided action given sufficient visual information in the graphical displays. With reduced visual cues we might predict an interaction between the systems leading to the influence of experienced effort on both perceptual awareness and visuomotor control. Future experiments in our laboratory will examine this prediction.

Utility of Virtual Environments for Studies of Perception and Action

The "real-world" performance found in the present studies supports the use of a virtual environment comprising large projection screens and a self-propelled treadmill for studies of space perception. The Treadport is a unique locomotion interface that allows the visual world to update continuously as a participant moves through large-scale space. Recent research with the Treadport has assessed the validity of horizontal forces applied by the tether on simulating gravity forces and biomechanical perception of slope (Hollerbach et al., 2000, 2001). However, the present studies are the first to assess visual perception of geographical slant and the influence of biomechanical information from slope forces on this perception. Our findings of large overestimation of slant in conscious perception and accurate visuomotor responses in all four experiments are consistent with several other studies that have used similar methodology but very different visual settings (Bhalla & Proffitt, 1999; Creem & Proffitt, 1998; Proffitt et al., 1995).

The Treadport allowed us to vary the nature of the translational movement experienced in each experiment. We first examined whether the amount of active exploration with respect to the hills would influence slant judgments. We found that the amount of active translation (no translation, visual translation, and real walking in Experiments 1, 2, and 3, respectively) over the hills when systematic forces were not included did not influence slant judgments. However, all of the experimental conditions allowed rotational flow as a result of head and torso movement. Although we would not predict that the rotational movement would provide additional information about depth to aid in slant judgments, it is likely to have allowed the participant to more strongly feel their presence within the virtual world by increasing their total field of view.

Manipulating one of the most notable features of the Treadport, the ability to simulate the forces and effort associated with walking uphill while the participant is actually walking on a level treadmill belt, led to an increase in perceptual slant estimations. These findings support the utility of virtual environment interfaces that allow for realistic interaction with the environment. Although previous studies (Bhalla & Proffitt, 1999) have made a correlation between the potential for action and the perception of slant, the present methodology allowed us to assess perception of slant after varying the amount and veridicality of experienced action. We provide confirmation that perception of geographical slant is influenced by information provided by our own actions. In all, the past and present studies of large-scale geographical slant have demonstrated independence and interaction between perceptual and action-based estimations of slant. We add to the understanding of the relation between perception and action by showing that effortful interaction with hill slant can change one's phenomenological perception of that hill, while a visually guided action response remains accurate and directly informed by the visual properties of the hill.

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