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Effect of Eye Height on Estimated Slopes of Hills

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Abstract

Several studies have shown that slopes of hills are greatly overestimated. We have recently demonstrated that the overestimates increase logarithmically as the end point of the domain to be estimated is increased. A theoretical analysis showed that a critical parameter is the angle between the observer's line of sight and the slope of the hill, when the observer fixates the far point of the required domain. The theory predicts that increasing the observers' eye height will increase this angle, thus reducing the overestimates. Here, we test that theory by having observers stand on a box to increase their eye height. Slope estimates for various ranges again followed a logarithmic function, with lower estimates at nearer distances compared with other observers standing directly on the surface of the hill. At larger distances, slope estimates with and without increased eye height converged.

vision slopes space perception

Introduction

Fundamental to perceptual psychology is the internal map of immediately surrounding space that everyone carries with them. Other perceptual processes are calibrated with respect to this map. Thus, it is important to know how this map functions, and especially what illusions it may incorporate. A wealth of work has investigated the sense of space on flat ground, but the investigation of how people deal with slopes is just beginning.

A consistent result has been a large overestimation of slopes, first formally described by Kammann (1967). The cognitive processes that underlie perception of the slopes of hills have been studied with proprioceptive and verbal measures (Proffitt, Creem, & Zosh, 2001; Proffitt, Stefanucci, Banton, & Epstein, 2003). Early reports found a proprioceptive estimate (adjustment of a palm board) to show little error, while verbal or conceptual estimates (matching with a paper model of the hill) were substantial (Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Differences between the proprioceptive and verbal measures have been attributed to two visual systems, a cognitive system (Bridgeman, Lewis, Heit, & Nagle, 1979) suffering from illusions while a separate sensorimotor system uses more accurate information to drive visually guided behavior (Bridgeman, Gemmer, Forsman, & Huemer, 2000).

Since the palm board requires manipulation of an object, it requires orientation to the board as well as the slope. Direct matching of the forearm with the surface of the hill with no intervening apparatus has found substantial though lower errors (Chiu, Hoover, Quan, & Bridgeman, 2011, Chiu, Thomas, Persike, Quan, & Bridgeman, 2014; Durgin, Hajnal, Li, Tonge, & Stigliani, 2010). In fact, Durgin and Li (2010) and Shaffer, McManama, Swank, Williams, and Durgin (2014) go a step further to show that proprioceptive slope estimates have been biased by a starting point that was always horizontal; when this restriction was removed, proprioceptive slope estimates were consistent with verbal estimates. These authors took proprioceptive measures after starting their observers at varying arm postures from horizontal to vertical, eliminating the starting-point bias of earlier studies.

What, then, is the critical variable that observers use to estimate the slopes of hills? One possible influence of distance on slope estimates originates with the effort hypothesis (Proffitt et al., 2003; White, Shockley, & Riley, 2013). If the perceptual system is informing the observer about a combination of the geometric reality and the anticipated effort in negotiating the observed slope, an overestimation of slope might result to warn about the difficulty of climbing the hill. This hypothesis predicts no increase in perceived slope with distance because each step requires about the same energy as the previous step.

Fatigue would not be relevant with the distances of a few meters that are considered here. Our longest distance of 16 m can be traversed by a healthy subject in eight paces requiring about 16 s. Our healthy undergraduates scale longer and steeper hills every day on our mountainous campus without difficulty. Moreover, our observers did not actually scale the slope, and in any case, the fatigue hypothesis does not predict logarithmic increases in perceived slope with distance. Hecht, Shaffer, Keshavarz, and Flint (2014) analyzed a number of previous experimental results, showing that the studies that used longer ranges found larger relative errors of slope estimation, contradicting the prediction of the effort hypothesis. Both Chiu et al. (2014) and Li and Durgin (2010) found a logarithmic increase in perceived slope with distance, each doubling of distance resulting in a constant increment in perceived slope. A logarithmic increase follows the same rules as a wide variety of other perceptual illusions but this does not explain the effect.

To explain the increase in slope estimates with increasing range, Chiu et al. (2014) presented a mathematical model based on *v'*, the perceived angle between the observer's line of sight and the contour of the hill *v*, defined at the distal end of the estimated range. Sedgwick (1986) pointed out the importance of this parameter in specifying distance to an object. Chiu et al. (2014) used this model to explain a logarithmic increase in judged slope with increasing range of a hill to be judged, defined as slope between the observer and a target. This angle is a linear function of distance over large differences in range and correspondingly large differences in slope estimates.

Li and Durgin (2009) made an observation consistent with this model; when an observer stands on a level road built into the contour line of a slope, standing on the edge of the road nearest the downhill slope and judging the slope downhill from the road yields lower slope estimates than standing on the opposite side of the road near the uphill slope and again estimating the slope downhill from the road. This observation is the opposite of what a danger hypothesis (Proffitt et al., 2001) predicts.

The *v'* theory makes a further testable prediction, that hills should be perceived as less steep when eye height is increased. The present article tests that prediction.

Experiment 1

Method

Observers

Thirty-five undergraduate students at the University of California, Santa Cruz, participated for partial fulfillment of course requirements, 20 in the experimental group and 15 in the control group. All participants were naive to the purpose of the experiment, had not participated in previous slope experiments, and had normal or corrected-to-normal vision and no physical impairments. All procedures were approved by the institutional review board of the University of California, Santa Cruz.

Stimuli and procedure

The experiment was carried out on a long paved slope with a uniform inclination of 12°. Traffic cones were placed 2, 4, 8, and 16 m from the base of the hill toward the apex. Each cone was marked with a number, so that observers could be directed to the appropriate cone to make their slope estimates without referring explicitly to distance. After signing an informed consent form, the observers were given the following instructions.

In the lab:

> “We will be going out to a hill a 3-minute walk away and judging its slope in degrees while standing on a box. A photo will be taken of you while on top of the box. This photo will be destroyed after we measure your eye height. Here is 0° [demonstrate with table surface], here is 90° [demonstrate with chalk board], here is 45° [demonstrate with arm].” Instructions for the control group were the same except that “while standing on a box” was omitted.

At the hill:

> While standing on this box, you will be estimating the steepness of this hill in degrees. You will be judging the slope between yourself and a series of traffic cones placed at varying distances. For each judgment, tell us the slope of the pavement in degrees between the pavement in front of you [point at pavement directly in front of the face edge of the box] and the base of the cone we specify [point at the base of cone].

Observers in the experimental condition stood on a sturdy wooden box (Grass Instrument Co., Quincy, MA) 37 cm high while making their slope estimates (Figure 1). They stood with their toes at the front of the box and made estimates of slope in a fully counterbalanced randomly assigned order for each of the four traffic cones. In the control condition, observers stood directly on the sloping pavement of the hill.

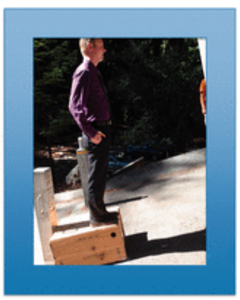

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Figure 1.

An observer standing at the base of the 12 hill with enhanced eye height.

Slope measures were taken in estimated degrees; proprioceptive estimates (matching the slope of the hill with a tilt board or with the forearm) were not taken because of the consistently high correlation between verbal and proprioceptive measures (Chiu et al., 2014; Proffitt et al., 2001, 2003). Moreover, verbal and proprioceptive measures coincide when care is taken to avoid starting-point bias, as reviewed above (Durgin et al., 2010).

Results

Three of our observers in the experimental group estimated the slope of the hill to be 90° at the 16 m distance. We interpreted this to be a fundamental misunderstanding of the instructions or the degree scale and eliminated them from the data analysis.

Figure 2 shows the error in slope estimates as a function of distance. Again the slope estimates follow a logarithmic function very closely (r^2 = .997), but with a steeper slope than was found for observers standing on the hill in the control condition. This result is consistent with the *v'* theory.

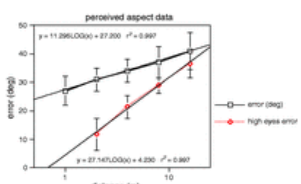

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Figure 2.

Semilog plot of mean error in slope estimate versus distance over which the estimate is made. Control data (“error,” squares) from observers standing on the slope are compared with the experimental condition data with enhanced eye height (“high eyes error,” diamonds). Straight lines are best-fit logarithmic functions.

Because eye height above the contour of the hill’s surface is a critical variable in our theory, we also correlated eye height with slope estimates across observers at each distance. The theory predicts a negative correlation between eye height and perceived slope because greater eye height results in a larger angle between gaze and hill contour. The effect should be strongest at the closest distances, where the increased eye height has the largest effect on the angle *v*. We found no significant correlations between eye height and perceived slope in the experimental condition, however. Each observer’s eye height was plotted against that observer’s subjective slope *v’* at each distance. Correlations *r* varied over a range from −0.027 to +0.176, $r^2 < .032$. This lack of correlation is accompanied by a small range of eye heights, however, for all observers were of similar height; all but three of them had eye heights between 140 and 160 cm, or when standing on the box between 177 and 197 cm from the ground surface, a range of 11%. Mean eye height in the experimental condition = 187.9 cm, *SD* = 9.63. The large constant increase in eye height due to the box had a large effect, as seen in Figure 2, but the small differences between observers had no additional effect.

There remains a concern that the differing estimates by each observer might be due to experimental demand. That is, if asked for four estimates, the observers might assume that the estimates should be different, even if they do not perceive the slope that way, and would thus give differing estimates. This possibility can be tested by considering only the first estimate from each observer. This estimate of course cannot be affected by a felt pressure to make an estimate different from the previous estimates.

Looking only at the first estimate made by each experimental observer still yields a monotonically increasing function of slope estimate versus distance, with errors ranging from 19° at the 2 m distance to 41° at the 16 m distance (Figure 3). These errors are even larger than the average errors plotted in Figure 2 where all data are included, but since the sample of first observations is small the possibility cannot be excluded that the discrepancy might be due to sampling error. Although the sparseness of the first-estimate data results in more noise and a poorer fit, the logarithmic function is a better fit to the data, $r^2 = .94$, than the linear function, $r^2 = .80$.

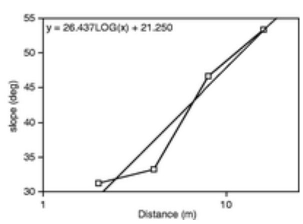

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Figure 3.

Semilog plot of slope estimates using only the first estimate from each of the observers in the experimental condition. Straight line is the best logarithmic fit.

Experiment 2

The first experiment compared slope estimates with enhanced height to slope estimates by observers standing on the surface of the slope, finding smaller errors with enhanced eye height but a faster increase in estimates as distance increased. The control group was run separately from the experimental group, however, at a different time. To control for order effects, a second experiment was executed with alternate assignments of observers from the same population: the first observer going to the standing condition, the second to the enhanced condition, and so forth. This experiment also serves as a replication of the first experiment.

Method

Observers

Alternating 33 observers chosen for the control and experimental groups resulted in 17 observers in the control group and 16 in the experimental group. The sample criteria were the same as in Experiment 1.

Stimuli and procedure

Instructions were the same as in Experiment 1 except that the observers were reminded at the hill before beginning their estimates that 0° represents flat ground and 90° represents a vertical cliff. With this extra precaution, none of the observers gave 90° estimates under any of the conditions. We also controlled for any possible experimenter effects by having the same experimenter giving the instructions in the same manner for all participants in both conditions. Each of the groups also received the same cone order. The cones were randomized within groups, but the same order between groups allows a direct between-group comparison.

Traffic cones were placed at 2, 4, 8, and 16 m from the observers' toes, and slope estimates by the two groups were elicited in a balanced order.

Results

Slope estimates under experimental (enhanced eye height) and control (standing on the slope) conditions were similar to those in Experiment 1 (Figure 4). Again the data closely fit logarithmic functions, reflecting Weber's law.

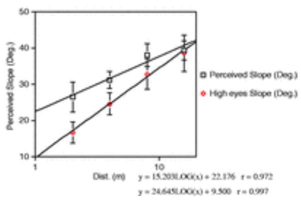

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Figure 4.

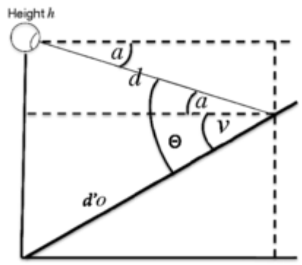
Semilog plot of mean error in slope estimate versus distance over which the estimate is made, in the format of Figure 2. Error bars are +/− 1 *SEM*. The top line of regression equations and *r* describes the control group, while the bottom line describes the experimental group.

Because the domains tested in this experiment were the same for both experimental and control groups, we were able to test the statistical significance of the differences in slope estimates using a split-halves method. The slope estimates at the shorter distances, 2 and 4 m, were significantly higher for the control group standing on the slope than for the experimental group with enhanced eye height ($t_{64} = 2.5$, $p = .015$). At the longer distances, 8 and 16 m, the two groups were not statistically significantly different ($t_{64} = 0.8$, $p = .434$). The results are consistent with the *v'* theory.

General Discussion

Replicating previous studies (Bhalla & Proffitt, 1999; Bridgeman & Hoover, 2008; Chiu et al., 2014; Durgin et al., 2010; Durgin & Li, 2010; Proffitt et al., 1995, 2001, 2003), observers greatly overestimated the slope of our hill at all distances. In our experiments, the error of verbal estimates increased by a constant amount for each doubling of the distance over which the estimate was made, defining a logarithmic function. The slope of this function (Figures 2 and 4) was steeper for observers with increased eye height, as predicted by the *v'* theory. For close targets, the hill appears less steep while standing on the box than while standing on the ground. For far targets where the distance to the target is large compared with the enhancement of eye height, the perceived slope is similar whether eye height is enhanced or not. The *v'* theory is based on the idea that the critical variable in subjective slope estimation is the angle of regard when the observer fixates the contour of the hill at the target distance (Figure 5). Anticipated effort, perceived danger, and other factors play only a minor role if any. Clearly, when the eye is elevated further, the angles *a* and *Θ* increase.

Figure 5.



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Geometry of the *v'* theory. An observer of height *h* stands on the left side of the diagram. The dependent variable *v'* is the observer's subjective slope of the hill over the distance d'_o at the slope *v*. Perceived slope *v'* is a linear function of the angle of regard *a* and the slope *v*. For derivation, see Chiu et al. (2014).

Hecht et al. (2014) investigated slope estimates at distances up to 128 m with a somewhat different design. They presented a wooden slope 1 m long at varying distances from their observers and asked them to judge verbally in degrees, as we did, or with a proprioceptive response similar to that used by Bridgeman and Hoover (2008) and Chiu et al. (2014).

Hecht et al. (2014) presented slopes of 15°, not very different from our 12° slope, and 45°, far steeper than any highway or walkway. At the 15° slope, they found an increase in verbal estimates of perceived slope with distance up to their 36 m distance (Hecht et al., 2014); slope estimates asymptoted at larger distances. Their data show a logarithmic pattern (Figure 6), replicating our logarithmic findings.

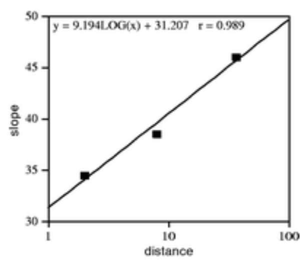

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Figure 6.

Perceived slope of a 1 m board at varying distances from the observers. Semilog plot. (Replotted data of Hecht et al. (2014), by permission.)

Our data combined with the Hecht et al. (2014) data demonstrate a dominance of geometric parameters over psychological factors; the effort hypothesis (Proffitt et al., 2003) predicts no change in perceived slope with eye height, as the effort required to scale a hill remains the same regardless of eye height. Anticipated effort might be modified indirectly, with greater eye height implying larger size that would either make climbing easier because the organism is larger relative to the distances to be traversed, or more difficult because more weight would have to be carried up the slope. In any case, the effort hypothesis would predict a horizontal line in Figure 1, rather than sloping upward as the geometric explanation of the *v'* theory predicts. This is because steps at greater distances require the same effort as steps at near distances; anticipated fatigue is not a factor for these short domains, as shown by the consistent logarithmic function at shorter and longer distances in our data.

In summary, we have found that increasing the eye height of our observers results in their estimating a hill as less steep than the estimates of similar observers standing on the hill's contour. Consistent with a geometry based on the angle between the observer's gaze at the target point and the contour of the hill, the estimates converge at greater distances where eye height differences become smaller relative to the domain of the slope to be judged.

Declaration of Conflicting Interests

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