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A slippery slope: Estimated slant of hills increases with distance

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Abstract. The slopes of hills tend to be greatly overestimated. Previous studies have found that slope estimates are significantly greater when estimated verbally than with a proprioceptive measure. It has yet to be determined whether these estimates are made for the entire extent of the slope, or whether the estimates in closest proximity are estimated using a different process. Since some parietal cortex neurons respond differently to objects within arm's reach, short-distance slope estimation may utilize these or analogous neurons. Alternatively, greater implied effort might make longer slopes seem steeper. We determined that both verbal and proprioceptive reports of slope are overestimates that increase logarithmically with distance from the observer, contradicting both theories. Consistent with previous work, proprioceptive estimates were more accurate at all ranges. Our results can be interpreted as a function of the angle between the observer's gaze and the plane of the hill, modified by depth cues available at only near distances.

Keywords: slope perception, proprioception, near-space, far-space, distance

1 Introduction

Our intuition is that the eyes convey a true geometric reality, that what we see is what exists in the physical world around us; in other words, we typically behave as Ramspberger's (1940) naive realists. However, we often fail to perceive the world as it truly exists, but rather perceive it in a manner that combines Euclidean distances with our own potential to interact with the external world. This so-called perceptual mixing has been demonstrated in a number of studies (Bridgeman, 2004; Bridgeman, Gemmer, Forsman, & Huemer, 2000; Jackson & Cormack, 2008; Post, Welch, & Bridgeman, 2003) that examine the distinct functions of the sensorimotor and cognitive visual systems and the use of information in each system.

Here we investigate slopes of hills using a verbal measure that probes perception, and also with a proprioceptive measure that requires a 1:1 correspondence between the slope of the hill and the inclination of the forearm. The cognitive processes that underlie these two tasks have been presumed to be revealed by the differences between proprioceptive and verbal measures observed in previous studies of estimated slopes of hills (Proffitt, Creem, & Zosh, 2001; Proffitt, Stefanucci, Banton, & Epstein, 2003). When asked to report the slope of a hill in a modality that is consistent with immediate motor action (proprioceptive), slopes are estimated more accurately than when the same people are asked to report the same slope in a modality more associated with long-term planning (either a verbal or conceptual modality). These results suggest that proprioceptive measures may differ from verbal measures due to underlying differences in the functions of the sensorimotor and cognitive systems, respectively.

Verbal and conceptual measures have been attributed to the ventral stream pathway: the 'what' stream (Ungerleider & Haxby, 1994), which is concerned with abstract reasoning and long-term planning (hereafter referred to as the 'cognitive system'; Bridgeman, Lewis, Heit, & Nagle, 1979). In contrast, the proprioceptive measure is thought to tap into the dorsal stream pathway (the 'where' or 'how' pathway; Ungerleider & Haxby, 1994)—the goal of which is immediate execution of motor output (Post et al., 2003), hereafter referred to as the 'sensorimotor system'.

Proffitt, Bhalla, Gossweiler, and Midgett (1995) asked participants to estimate the slope of a hill in one of three ways: verbally, proprioceptively, and conceptually. When making *verbal estimates*, participants provided an estimate in degrees while observing a slope. When making *proprioceptive estimates*, the same participants adjusted a tilt board with the palm of their hand, and when making *conceptual estimates*, participants adjusted a paper disk so that a triangular segment best represented the slope of the hill. The verbal and conceptual measures were found to overestimate the actual slant, while the proprioceptive measure did not.

In these studies participants based their estimates of slope on the entire range of a slope from its base to its apex, while observing the slope from a flat station point. To date, there is no research on whether estimates of slope change across the span of the slope from distances near the observer to those more distant. Estimates based on longer distances, such as those performed in previous studies, would seem to be more likely to reflect the interaction between the long-term planning mechanism of the cognitive system and the visual perception of the slope, producing the overestimates observed. Given that neurons in the parietal cortex have been found to respond differently to locations or objects within arm's reach rather than to locations or objects further afield (Andersen, 1989; Andersen, Essick, & Siegel, 1985; Graziano, Yap, & Gross, 1994), we reasoned that an analogous system might exist for estimates of slope in one's immediate periphery. Do people estimate slope differently if it is within their next step rather than many steps away?

It has previously been shown that attention to space immediately adjacent to the body may be partly separated from attention to space farther from the body. Patients with unilateral lesions to the parietal or frontal cortices have been discovered, who are able to detect a stimulus presented alone to either the ipsilesional or contralesional side, but fail to report the same stimulus presented to the contralesional side when a concurrent stimulus is presented on the ipsilesional side (Bender, 1952). This research is relevant to the hypotheses explored here, in that this 'extinction' effect occurs only for stimuli presented very near to a patient's body, and does not generalize to locations further afield (Cowey, Small, & Ellis, 1994; Di Pellegrino, Ladavas, & Farne, 1997; Halligan & Marshall, 1991; Ladavas, Pavani, & Farne, 2001; Ladavas, Zeloni, & Farne, 1998). To produce maximum extinction, the competing stimuli can be of different modalities (eg visual, auditory) but must be presented in the space near the body.

Other research has provided evidence for premotor cortex neurons that respond differentially to objects that are within reach and available for immediate physical interaction (Graziano et al., 1994). These neurons respond when the object is 'available' or reachable, but do not respond to the same object presented at a distance that is out of reach. Furthermore, when an object placed out of reach is made available for immediate action through the use of a prosthesis, estimates of the distance to that object decrease (Witt, Proffitt, & Epstein, 2005). This finding suggests that it is the so-called 'reachability' of the object or one's ability to immediately interact with the surrounding environment that drives differences in visual processing. If a similar mechanism is involved in slope perception, this predicts a break in the distance-versus-slope curve when the distance is immediately reachable. In the present study we explore whether an analogous system governs estimates of slope as well.

Another possible influence of distance on slope estimates originates with the effort hypothesis (Bhalla & Proffitt, 1999; Proffitt et al., 1995). More anticipated effort in climbing a longer slope might lead to steeper slope estimates by the cognitive system. The effort hypothesis predicts a smooth linear increase for the short distances that we investigate here, as each step takes about the same amount of energy as the preceding step for short slopes (Bobbert, 1960).

In order to address these questions, we adapted the method of Proffitt and colleagues (Bhalla & Proffitt, 1999; Proffitt et al., 1995, 2001, 2003) to contrast proprioceptive and verbal estimates of slope based on the area immediately in front of the observer compared with the entire surface of the hill (experiment 1), at a range of distances from the observer (experiment 2), and a final experiment to control for varying lengths of judged hillside along a slope, which addresses the confound of distance and length of segment used for the estimation (experiment 3).[1]

2 General method

2.1 *Stimuli*

Hills on the campus of the University of California, Santa Cruz were chosen based on the following criteria: (a) relative absence of foot traffic; (b) unobstructed by foliage or construction and closed to vehicular traffic; (c) long enough that the top of the hill would be well above eye height for participants standing on the slope at its base; and (d) fairly uniform slope, defined as having an even surface with no major changes in inclination, direction, texture dips, or bumps along its surface. These criteria limited the effects of prior experience with the hills and avoided introduction of systematic bias conferred by deviations to the uniformity of the surface. Hills were viewed while the participant stood at the base of the hill, facing the apex, in daylight. This is a departure from prior experiments, in which participants viewed the slope from a flat vantage point and not on the surface of the slope itself. While this provides an additional proprioceptive cue about the slope of the hill, it is required in order to allow the slope to be reachable to the participants. Measures of true incline were calculated using professional surveying techniques.

2.2 *Measures*

Two methods of recording slope estimates were used in experiments 1 and 2: a verbal and a proprioceptive measure. Because Proffitt and colleagues (Proffitt et al., 1995, 2001, 2003) consistently failed to find a significant difference between conceptual and verbal estimates, we determined that both modalities likely stem from the same cognitive system, and therefore recorded only verbal estimates of slope.

For the proprioceptive estimate, participants were asked to hold their elbow against their torso with the forearm perpendicular to the body, then raise or lower it to match the slope of the hill. This adaptation of Proffitt and colleagues' 'tilt board' measure eliminates any proprioceptive feedback or resistance, by requiring participants to rely on body posture alone as a basis for proprioceptive estimation. Durgin and colleagues (Durgin, Hajnal, Zhi, Tonge, & Stigliani, 2010a, 2010b) independently developed a nearly identical method, which they have found to be quantitatively more effective in measuring proprioceptive slope estimates than traditional tilt board methods, which is why we use this measure instead of a tilt board. Participants were instructed to gaze at a predefined fixation marker on the surface of the hill, and only on the hill, to prevent them from using visual feedback of how well their arm matched the slope to guide their estimate. We were prepared to discard data collected from participants who looked directly at their forearm while performing the estimate, but no participants did this.

[1] Some of the findings from experiments 2 and 3 have been previously presented in a brief report (Bridgeman & Hoover, 2008) and a conference proceedings paper (Chiu, Hoover, Quan, & Bridgeman, 2011), respectively. These prior reports did not detail either experiment to the extent of the current manuscript and were presented in a different theoretical context than our current discussion. Bridgeman and Hoover (2008) presented partial results from experiment 2 only, without curve-fitting or theoretical analysis, as part of a paper on processing spatial layout. Chiu et al. (2011) was not a peer-reviewed publication.

The large deviations of arm posture from actual slope corroborate that participants did not use visual matching. A digital photograph was taken of the forearm using a camera on a leveled tripod at elbow height. These photographs were used to determine the angle of the arm in Adobe Photoshop using the 'measure' tool.

2.3 *Procedure*
Participants met the experimenters in the lab and accompanied them to each of the appropriate slopes. Prior to performing any estimation, participants were instructed on both the proprioceptive and the verbal measures. The experimenter demonstrated estimates using the proprioceptive measure at 0°, 45°, and 90°. Participants were then asked to demonstrate these same angles using the proprioceptive measure, and without looking at their forearms to check their understanding of the task. All of them successfully performed these demonstrations prior to continuing with the experiment.

3 Experiment 1

The purpose of this experiment was to examine the differential effect of space on slope estimations. In this experiment participants provided both verbal and proprioceptive estimates for two distances, near (1 m) and far (15 m), on four hills, varying in both inclination and surface texture, to investigate the difference between estimates of slope in peripersonal and extrapersonal space.

3.1 *Method*
3.1.1 *Participants.* Ten undergraduate students from the University of California, Santa Cruz participated in this experiment. All received credit in partial fulfillment of course requirements and were required to have normal or corrected-to-normal vision along with no major physical impediments. None had participated in prior distance or slope experiments. Participants were randomly assigned to counterbalanced order of estimations to avoid sequence effects.

3.1.2 *Stimuli and procedure.* Two of our four hills were unpaved, 'natural' hills, while two had paved pathways along the surface. This allowed an analysis of the surface texture to be performed. The inclines of these hills were 6°, 9°, 10°, and 12°. Traffic cones were placed in two locations on the surface of the slope, either 1 m from the participants' feet (approximately one long step for most participants) or 15 m from their feet. These distances were used for each participant to give both a 'near-space' and a 'far-space' estimate for each hill, in both the verbal and proprioceptive modalities, for a total of four estimates per participant per hill. Slope measures were recorded in degrees. After the participant had provided those four estimates for a given hill, he or she accompanied the experimenter to each subsequent hill for a total of 4 hills and 16 estimates per participant. The order of hill estimated as well as the order of verbal or proprioceptive measure and near-space and far-space were all counterbalanced.

3.2 *Results*
Raw estimates of slope were transformed into error data by subtracting the objectively measured slope angle from each estimate of slope for all analyses. In order to carry out a planned contrast comparing paved surfaces with unpaved surfaces, error data for each participant from each of the two paved hills and the two unpaved hills were averaged separately before analysis. The final data were analyzed in a 2 (measure) × 2 (distance) × 2 (surface) repeated-measures ANOVA.

For verbal measures, the mean slope overestimate was 22.9° for far-space (SD = 12.9°) and 14.8° (SD = 13.3°) for near-space (figure 1). Errors were much smaller for the proprioceptive measure; the mean overestimate was 10.7° (SD = 4.1°) for far-space and 9.3° (SD = 2.7°) for near-space. The mean overestimate averaged across near-space and far-space was 18.8° for the verbal measure (SD = 12.6°) and 10.0° for the proprioceptive measure (SD = 2.6°).

This main effect was significant ($F_{1,9} = 6.19$, $p = 0.035$), with the verbal measure showing more overestimation than the proprioceptive measure. For both proprioceptive and verbal measures combined, the mean overestimate was 16.8° in far-space (SD = 7.7°) and 12.0° in near-space (SD = 7.5°); this main effect was also significant ($F_{1,9} = 6.66, p = 0.024$) (however, we note that this main effect should be interpreted with caution, given the measure × distance interaction reported below).

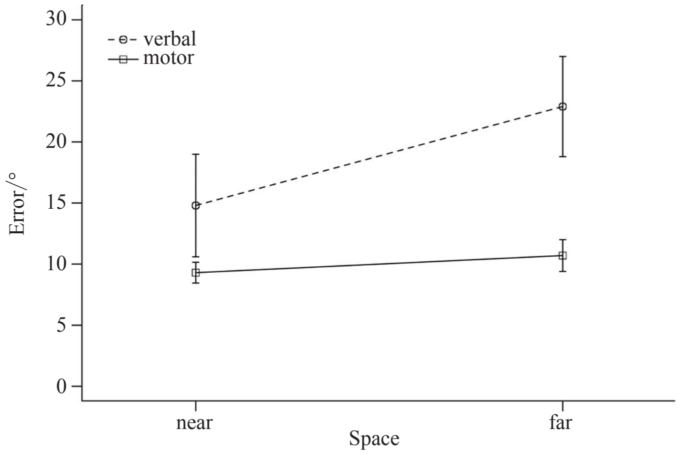

Figure 1. Results from experiment 1. Verbal (circles with a dotted line) and motor (squares with a solid line) slope estimates for a range extending from the participant to a near marker (1 m) and a far marker (15 m) for both paved and unpaved hills. Error bars are the standard error of the mean.

Summing over measures, the mean overestimate for paved hills was 17.4° (SD = 9.4°), which was significantly greater than the mean overestimate for unpaved hills at 11.4° (SD = 6.4°) ($F_{1,9} = 6.15, p = 0.035$). In addition to the main effects, there was also a significant interaction between distance of estimation and type of measure ($F_{1,9} = 12.83, p = 0.006$), with the verbal measure differing from the proprioceptive measure when only slope was estimated over the 15 m distance (figure 1), and only the verbal measure seemed to be different for the different distance estimations. There were no other significant interactions.

3.3 *Discussion*

The results of experiment 1 replicated the now well-established pattern that verbal estimates of slope show much greater overestimation of the actual slope than proprioceptive measures, when estimates are made over the entire distance of a hill. However, the results also demonstrate that this effect does not appear to hold—or is at least much weaker—when estimates are made at short range, where verbal estimates were much closer to proprioceptive estimates, and the difference between the two was not statistically significant.

This finding of a difference in verbal estimates at near and far distances adds to the literature on slope perception, but does not in and of itself adjudicate between the peripersonal space hypothesis and the calculated effort hypothesis. The peripersonal space hypothesis can account for this difference as the result of outputs from two neuronal systems, with the more accurate estimate in the near condition resulting from a neuronal system for an individual's immediate actionable vicinity, and the less accurate estimate in the far condition resulting from a neuronal system for distances that are not immediately available for action. Our data could also be accounted for by the calculated effort hypothesis, since the degree of overestimation may track the potential energy expenditure for traversing the observed space. Not only can both of these hypotheses account for the data, but they are not necessarily mutually exclusive, as the neuronal system for tracking space further from one's immediate vicinity may be calculating expected energy expenditure.

The significantly greater slant estimates given when viewing a paved slope versus an unpaved slope tell us that ground surface affects slant perception. This is consistent with findings that show ground-surface information influences judged distance (Ooi & He, 2007; Ooi, Wu, & He, 2006). This occurs because ground-surface texture provides various depth cues (eg binocular disparity, cast shadow, and nested contact information) that an otherwise smooth surface does not.

4 Experiment 2

Experiment 2 was designed to test whether there is a discontinuity between slope estimates of one's peripersonal space and further distances and, if so, whether estimates of slope outside of one's immediate peripersonal space track expected energy expenditure. To test this, we asked participants to give proprioceptive and verbal estimates of slope on a single hill at five different distance intervals.

If the different verbal estimates in experiment 1 at near versus far distances were the output of one system that was simply tracking differential effort necessary to interact with different distances, this would predict that overestimates of slope should show a smooth linear increase as the distance over which the estimate is made increases. If the estimates were the output of two different neuronal systems, this would predict a discontinuity in estimate errors as the distance increases from one's immediately actionable environment (eg 1 m), to distances just beyond that environment (eg 2 m or more). If there are two separate systems involved in making these estimates, and the system for far-space is calculating effort, this predicts the same discontinuity, but predicts that, at distances beyond this discontinuity (eg 2–16 m), estimate errors will show a smooth linear increase as the distance of the estimate increases.

4.1 *Method*

4.1.1 *Participants.* Fifteen undergraduate students from the University of California, Santa Cruz participated in this experiment for partial fulfillment of course requirements. 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.

4.1.2 *Stimuli and procedure.* In this experiment we used a single paved hill in order to provide the most visually uniform texture gradient for estimation and to induce larger errors, as it is the errors that are most informative to our interests. Participants stood on a long paved slope with a measured inclination of 12°. Traffic cones were placed 1, 2, 4, 8, and 16 m from the base of the hill towards the apex. Each cone was marked with a number, such that participants could be easily directed to the appropriate distance to inform estimates. As with experiment 1, the hill was tested and verified for uniformity. Tips of the traffic cones constructed a straight line, which was measured to be within 1 cm of complete uniformity when connected, as assessed via digital photography and Adobe Photoshop.

Participants made estimates of slope in a fully counterbalanced randomly assigned order. They were first asked to estimate the slope using either the proprioceptive or the verbal measure while concentrating on the distance between themselves and one of the five randomly assigned markers on the slope. Then they would step out of the location where the estimates were made, execute one full rotation to reorient, and step in again to make the next judgment until each participant had made both a verbal and proprioceptive estimate for each of five distance conditions resulting in a total of ten estimates per participant.

4.2 *Results*

Results for the verbal and proprioceptive measures are shown in figures 2 and 3. We see that the main effect of distance on both verbal and proprioceptive estimates averaged together ($M = 29.9°$, SD = 6.4°) was significant ($F_{1,8} = 5.78$, $p = 0.043$), with the verbal measure ($M = 34.1°$, SD = 5.9°) showing more overestimation than the proprioceptive measure ($M = 25.7°$, SD = 3.4°) as distance increases. A closer inspection reveals that verbal estimates increased significantly across distance ($F_{1,3} = 24.33$, $p = 0.016$), as predicted by experiment 1. Interestingly, although previous reports (Bridgeman & Hoover, 2008) and our experiment 1 did not find a significant effect of distance (near-space vs far-space) on proprioceptive estimates, the results from experiment 2 reveal that though proprioceptive estimates are significantly more accurate than verbal estimates, they do differ significantly as viewing distance increases ($F_{1,3} = 19.04$, $p = 0.022$). To test this effect, we utilized a one-sample t-test that compared the linear slope estimates of each observer and found that mean estimate errors are significantly greater than zero for proprioceptive estimates ($t_4 = -16.87$, $p < 0.001$), meaning that proprioceptive estimates are affected by an increase in viewing distance.

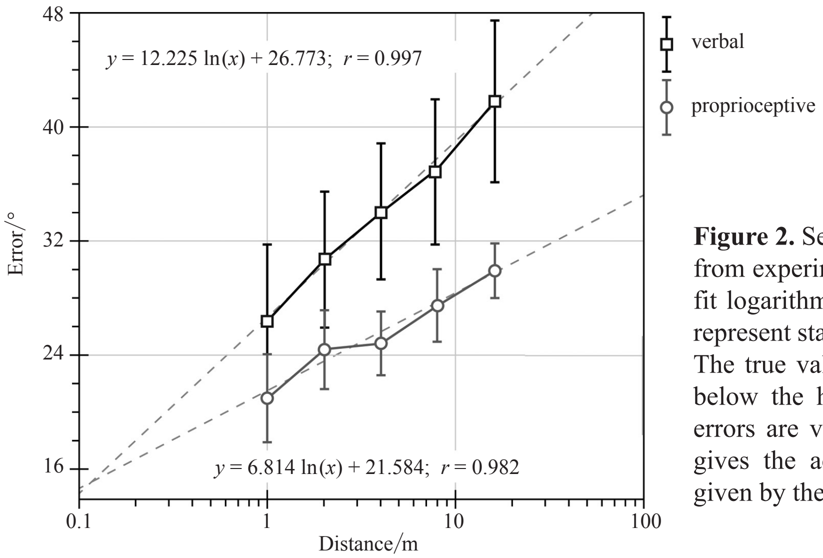

Figure 2. Semilog plot of range data from experiment 2 results with best-fit logarithmic functions. Error bars represent standard error of the mean. The true value of the slope, 12°, is below the horizontal axis, so only errors are visible. The vertical axis gives the actual average estimates given by the participants.

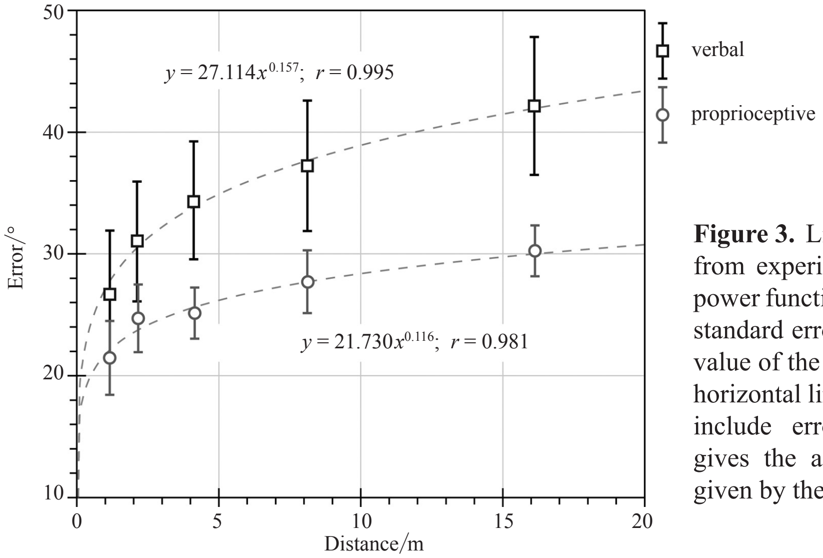

Figure 3. Linear plot of range data from experiment 2 with the best-fit power functions. Error bars represent standard error of the mean. The true value of the slope, 12°, is given by a horizontal line, so all slope estimates include errors. The vertical axis gives the actual average estimates given by the participants.

Observers again greatly overestimated the slope at all distances with the verbal measure, consistent with previous studies (Bridgeman & Hoover, 2008; Durgin et al., 2010a, 2010b; Proffitt et al., 1995, 2001, 2003). Although it is clear that the error of verbal and proprioceptive estimates increased by a constant amount for each doubling of the distance over which the estimate was made, it does not appear that the pattern is well represented by a simple linear function. Figures 2 and 3 fit the results of experiment 2 with a Weber–Fechner logarithmic growth curve (figure 2) and a Stevens power function (figure 3).

Figures 2 and 3 show that the Weber–Fechner logarithmic growth curve ($r^2 = 0.997$) (figure 2) and Stevens power function ($r^2 = 0.995$) (figure 3) both fit the data well for verbal estimates. The functions that fit the data increase smoothly from the closest distance to the furthest, fitting continuous logarithmic or power functions very well throughout the entire range tested, such that, as distance from the observer increases, the discrepancy between geometric reality and verbal estimates of slope increases. The proprioceptive measure yielded similar results with good fits for both the logarithmic ($r^2 = 0.982$) (figure 2) and power functions ($r^2 = 0.981$) (figure 3), but with consistently smaller slopes and less average error from the true slope of the hill.

4.3 *Discussion*

The results from experiment 2 were inconsistent with a two-systems account for near-space versus far-space, which would have predicted a discontinuity in the function as the systems traded off, once the distance became large enough (ie from 1 to 2 m). It is apparent that this is not the case with our data. Interestingly, the functions that best fit the data's smooth increase throughout the entire range tested (1–16 m) appear to be continuous, but not linear, and are best fit by either power or logarithmic functions (see figures 2 and 3). This result makes our illusory slope measures consistent with many other illusions that fit the Weber–Fechner law.

Even though the increase in errors over distance was continuous, the functions that best fit the data are also inconsistent with an effort hypothesis, which predicts at most a linear increase in perceived slope as distance increases. Another independent line of research by Durgin et al. (2009) and Durgin, Klein, Spiegel, Strawser, and Williams (2012) also recently obtained results inconsistent with the effort hypothesis. They found that the effect of increased perceived effort and resulting increase in slope estimation from wearing a weighted backpack disappears when a neutral explanation for the backpack is provided. The result implies that the original report of increased slope estimates while wearing a heavy pack (Bhalla & Proffitt, 1999) was likely the result of demand characteristics of the experiment rather than a function of effort; in other words, judgment biases appear to be the result of social, not physical or cognitive, demands of the experiment. Furthermore, Shaffer, McManama, Swank, and Durgin (2013) found when controlling for experimental demand there is no difference in verbal or motor estimates of slope between low and normal blood sugar levels; blood sugar level was previously observed to indicate the body's available energy resources and affect slant overestimation (Schnall, Zadra, & Proffitt, 2010). Taken together, these findings cast doubt on the effort hypothesis for verbal overestimations of slope.

The results of experiment 2 contradict both theoretical possibilities considered thus far, but before we present a new theoretical explanation for the patterns observed in this study, an alternative explanation introduced by a confound must be ruled out. In experiment 2 further distances were also estimated over longer spans of the hill, which means that the observed increases in estimate errors as distance increased may have been due to the lengths of the segments used for estimating the slope at different distances, rather than due to the distance from the observer. Experiment 3 was designed to rule out this alternative hypothesis.

5 Experiment 3

The purpose of this experiment was to investigate the role of distance on error of verbal and motor slope estimation while controlling for observed segment length. To unconfound length of observed segment from distance from the observer, the lengths of the to-be-estimated slope segments were varied independently from the distance to the observer. We introduce the variable of length of segments and distance from the observer in four predetermined intervals (0–1 m, 1–8 m, 8–15 m, and 15–16 m, with 0 m defined as the position of the observer) with a focus on the near (0–1 m) and far segments (15–16 m); the remaining two segments (1–8 m and 8–15 m) were simply used as distractors to prevent order effects. This design allowed us to evaluate whether it was the logarithmic pattern of the ranges tested or proximity to the observer that drove the logarithmic relationship between distance and slope estimate errors observed in experiment 2.

5.1 *Method*

5.1.1 *Participants.* Forty-eight students from the University of California, Santa Cruz were naive to the purpose of the experiment, had not participated in previous slope experiments, and had normal or corrected-to-normal vision as well as no physical impairments. Participants were thirty males and eighteen females with ages ranging from 18 to 23 years and a mean age of 19.4 years. For participating, subjects received partial course credit towards an introductory psychology course.

5.1.2 *Stimuli and procedure.* The test site was the same 12° slope used in experiment 2. Proprioceptive and verbal data were collected as detailed in section 2. Participants judged the four segments in a randomized counterbalanced order.

5.2 *Results*

Following our predictions from previous experiments, participants increased their verbal and their proprioceptive slope judgments as distance from the observation point increased. For verbal measures, the mean slope overestimate was 15.6° (SD = 16.9°) for the 0–1 m segment and 19.7° (SD = 16.4°) for the 15–16 m segment. Errors were much smaller for the proprioceptive measure; the mean overestimate was 8.1° (SD = 9.6°) for the 0–1 m segment and 13.9° (SD = 9.5°) for the 15–16 m segment.

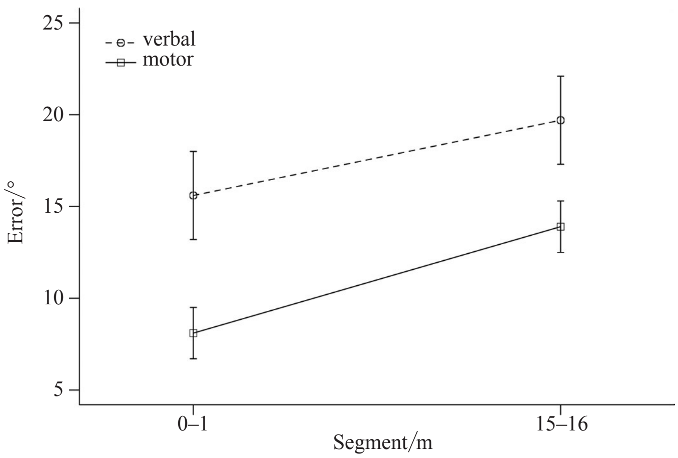

Figure 4. Results from experiment 3. Verbal (circles with a dotted line) and motor (squares with a solid line) slope estimates for a near segment (0–1 m) and a far segment (15–16 m). The vertical axis shows slope estimates in excess of the 12° slope of the hill. Error bars represent standard error of the mean.

The mean overestimate averaged across segments was 12.0° for the proprioceptive (motor) measure (SD = 9.1°) and 18.9° for the verbal measure (SD = 15.1°). This difference was significant ($F_{1,47} = 8.85$, $p = 0.005$), replicating our result that the verbal measure produces steeper estimates than the proprioceptive measure. For proprioceptive and verbal measures combined for the two segments of interest, the mean overestimate was 11.8° (SD = 14.2°) for the 0–1 m segment and 16.8° (SD = 13.6°) for the 15–16 m segment. The 5° difference was significant ($F_{1,47} = 14.04$, $p < 0.001$), showing that far-space produced steeper estimates than near-space for both modalities. Thus, in addition to replicating our previous results with a new sample of observers, we have determined that it is likely the distance of a slope sample from the observer, and not the length of the sample, that is critical in the distance–slope effect.

6 General discussion

Our first experiment replicated the phenomenon that human participants greatly overestimate the slopes of hills, but added the finding that this effect depends on the distance from the observer as well as the texture of the hill. In both verbal and proprioceptive measures errors increased with distance, though they increased more when measured verbally. Furthermore, errors were much smaller for a short (1 m) segment of slope contiguous with where the participant stood than for a longer segment starting from the same position. We used these results in experiment 2 to simplify our design and investigate the distance effect more closely, finding a very precise fit to both logarithmic and power-function models for both measures. In the third experiment we ruled out an alternative explanation for the results in experiment 2 by eliminating a confound of distance and length of segment estimated, and found that the distance from the observer, not the length of the segment, influences increases in slope estimation.

In general, we found that the changes of methodology allowed a consistent replication of previous findings, with new results indicating that space is estimated differently at different ranges. Though we replicated the overestimation of real-world slopes originally reported by Proffitt et al. (1995), we also found a significant overestimation of slopes by our proprioceptive measure that Proffitt et al. did not report. One possible reason for this is that our participants, unlike Proffitt's, stood on the slope rather than on level ground in front of it. While observers in Proffitt's experiments had a horizontal reference point, ours did not; even proprioception from their leg muscles provided information that they were standing on a sloping surface. This proprioceptive information is likely to have been integrated into estimates of slope in both cognitive and sensorimotor systems. Despite this proprioceptive information, however, participants continued to consistently overestimate the slopes.

Another possible explanation for the discrepancy between our proprioceptive measure and Proffitt et al.'s (1995) is that we used a hands-free measure while Proffitt et al. used a palm board. As mentioned above, Durgin and colleagues (2010a, 2010b) have shown the palm board to be an unreliable and biased proprioceptive estimator of slope, and may have decreased error in Proffitt's original studies due to haptic feedback provided by the tilt board. Durgin et al. (2010a, 2010b) tested a slope-matching posture that was nearly identical to our proprioceptive method and found it to be a much more effective and sensitive method for providing proprioceptive measures. They showed that wrist-flexion palm boards used by previous slant perception studies (Bhalla & Proffitt, 1999; Proffitt et al., 1995, 2001) grossly underestimate the orientations of near, reachable surfaces, as well as outdoor hills. Palm board measures were found to produce biased and noisy estimates compared with free hand elbow flexion, which was found to be fairly accurate (Durgin et al., 2010a, 2010b).

Our results were inconsistent with both theories we set out to test: a dual neuronal systems model and a perceived effort model. We hypothesize that slope overestimates found here were instead the result of a three-dimensional extension of Gogel and Tietz's (1973, 1979) specific distance tendency, as elaborated by Ooi et al. (2006). Ooi et al. measured apparent distances and directions of point targets at floor level in darkness, and found that participants made accurate directional estimates but underestimated target distances. The distance underestimation error increased with distance of the target, corresponding to an implicit ground slope of 12.4°. Using a method introduced by Loomis and Philbeck (1999), they also showed that participants indeed perceive the intrinsic surface as sloping. Their method required participants to adjust two arms of an L-shaped target to appear equal in length; one arm was in the frontoparallel plane, while the other, adjustable arm extended in depth. Participants adjusted that arm as though the figure were mounted on a sloping surface. Interestingly, in a follow-up study by Ooi and He (2007), where observers made slant estimates on grassy surfaces in a more optimal full-light condition, they found smaller overestimates compared with previous dark room studies (Ooi et al., 2006).

This implicit slope might explain why the minimum errors even for our proprioceptive measure were about 10° at ranges corresponding to Ooi et al.'s (2006) maximum distance of 7.5 m. That is, if Ooi et al.'s intrinsic bias were added to the true slope of a hill, the psychophysical estimates that we obtained would result. At near distances other information sources are available in the natural environment, reducing the errors. These sources, such as stereopsis, become systematically less reliable as range increases; participants are then forced to rely more on the intrinsic slope, and errors increase (Ooi & He, 2007).

Further, Ooi et al. (2006, figure 2b) found that the intrinsic slope increases with distance, perhaps explaining the increasing slopes reported by our participants with increasing range. Their range varied only from 1.5 m to 7.5 m, but our range of 1 m to 16 m brackets this range, and in experiment 2 we found continuous functions throughout the smaller range and extending in both directions into our range. Thus the principles governing our participants' behavior within Ooi et al.'s (2006) range extend to our entire range, though further psychophysical work will be necessary to integrate those results with ours quantitatively.

6.1 *Angle of regard*

Participants in our experiments stood on the surface of the hills, which means that there is no distance from the participants' position and the start of the slope. This experimental design allows us to analyze the data in linear terms as the angle between the slope of the hill and the angle of regard. This is illustrated in figure 5, where m is the height of the eye above the ground surface, d is the distance from the eye to the ground surface at a given distance x_0, υ is the slope of the hill, $h(x_0)$ is the height of the eye above the ground surface (where the observer is standing) at the distance x_0, and d' is the distance from the observer's feet to the point he or she is looking at measured along the slope of the hill (eg 1 m, 2 m, 4 m, 8 m, 16 m).

This geometric analysis of the observer/hill environment can yield further insight into the information that the observers use to make their slope estimates. Figure 5 shows the relationship of the observer's angle of regard, α, to the slope of the hill υ at the point where the gaze meets the hill. The figure shows the general case for a hill whose slope can vary with distance. For the current analysis the situation can be simplified because d'_0 and d'_1 will coincide for a hill of constant slope; the distances d'_0 are the independent variables of measured distances on the hill from the observer to the respective traffic cones.

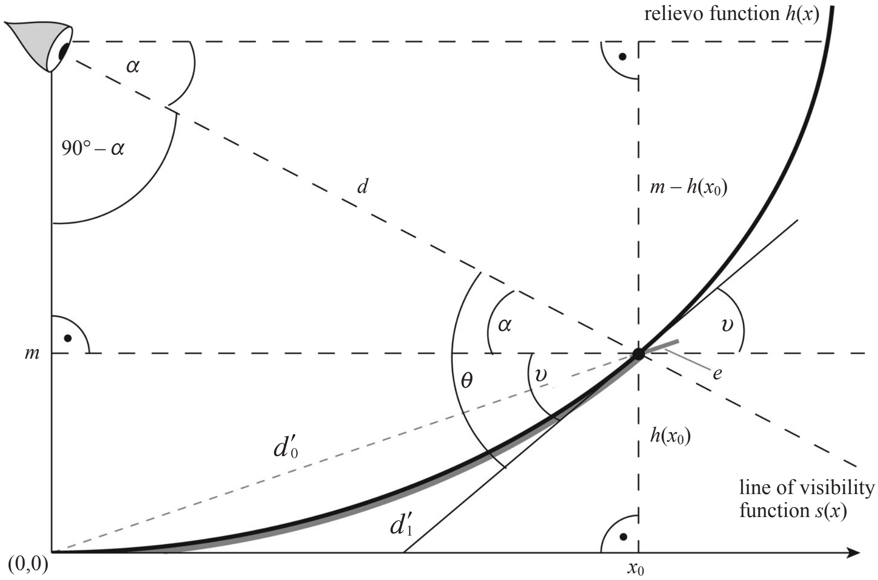

Figure 5. The relationship of a slope to observers' angle of regard. m is the height of the observer standing at the base of the hill, 170.4 cm based on the average height of American men and women between 20 and 29 years of age (McDowell, Fryar, Ogden, & Flegal, 2008). For a hill of constant slope, $d'_0 = d'_1$ is the distance along the surface of the hill and θ is the angle between the slope of the hill and the angle of regard.

To calculate d', we first divide it into two components; angle α is the angle between the line of regard, d, and the horizontal at the point where the line of regard meets the hill, while angle υ is the slope of the hill. Then:

$$x_0 = d'_0 \cos \upsilon \, ;$$

$$h(x_0) = d'_0 \sin \upsilon \, .$$

By the Pythagorean theorem,

$$d = \{x_0^2 + [m - h(x_0)]^2\}^{1/2} \, ,$$

and the angle of regard is defined as:

$$\alpha = \sin^{-1} \frac{m - h(x_0)}{d} \, .$$

With this we can find $\theta = \alpha + \upsilon$. Now we can calculate the values in table 1, using our data from experiment 2:

Table 1. Table of the calculated values given horizontal distance of hill from eye, x_0, and slope of hill at the point where the observer's gaze meets the hill, d'_0, for height of the eye above the ground surface, $h(x_0)$, distance of hill surface from the eye, d, observer's angle of regard, α, optical slant, θ, and the perceived slope of the hill from experiment 2, υ'.

d'_0	x_0	$h(x_0)$	d	α	θ	υ'
1	0.982	0.191	1.804	57.028	68.028	27
2	1.963	0.382	2.367	33.963	44.963	31
4	3.927	0.763	4.038	13.474	24.474	34
8	7.853	1.526	7.855	1.295	12.295	37
16	15.706	3.053	15.764	–4.909	6.091	39

In table 1 the distances d'_0 are the independent variables of measured distances on the hill from the observer to the respective traffic cones and the angles in the rightmost column are the slope estimates from experiment 2. The remaining values are calculated from the equations above. The resulting plot in figure 6 shows the angle between the direction of gaze and the contour of the hill as a function of the distance of the observation point, revealing a linear and slightly decreasing function.

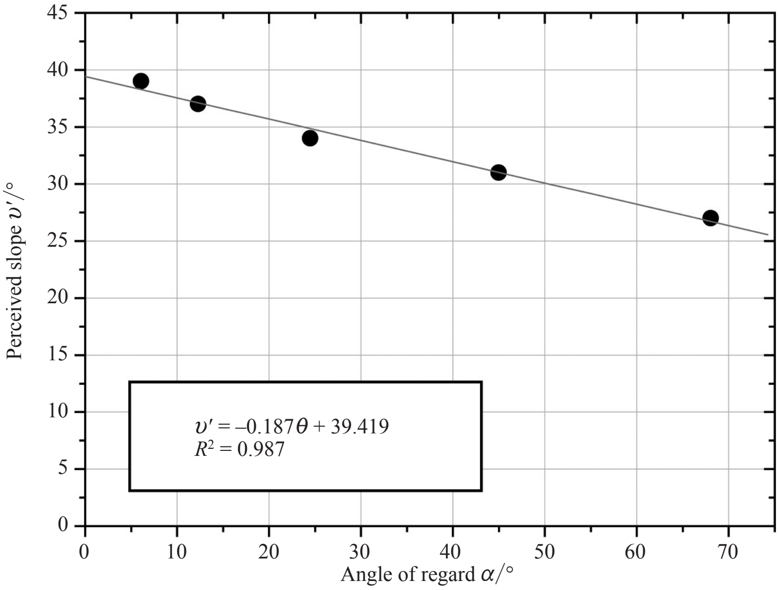

Figure 6. Fit of the perceived slopes of the hill with the angles of regard relative to the true slope.

The equation is derived solely from the physical structure of the hill and the observer's position on it. Thus the good fit suggests that it is the angle between the direction of gaze and the slope of the hill that the observers are using to make their slope estimates. If the function is extrapolated to the observer looking directly downward, the perceived slope becomes approximately 12°, which corresponds to the 12° slope of the tested hill. Subsequently, the subjective perception that the slope right under one's feet is not particularly steep is fully accounted for with this analysis. Another conclusion from this analysis is that cognitive (verbal estimate) and sensorimotor (proprioceptive arm position) measures both operate throughout the range tested, without interaction.

Our findings support the theory that perceived slope is the result of the intrinsic error found by Ooi et al. (2006), combined with observer's angle of regard. This suggests that information based on the angle of regard is combined with information about intrinsic slope and filtered through the sensorimotor and cognitive systems to produce two separate, measurable estimates of slope, assessed by our verbal and proprioceptive measures. These two measures use the same visual information to yield distinct estimates based on the functions they serve, either a long-term planning function and the hypothetical traverse across terrain or the short-term execution of a possible next step.

More recently, Li and Durgin (2010) parametrically assessed perceived slant at varying distances (1–16 m) and slants (6–36°), using both a verbal report and an implicit measure of optical slant via shape perception or aspect ratio perception for shapes on slanted surfaces in a virtual environment; optical slant is the same as what we refer to as angle of regard. Angle of regard, α, also known as *gaze declination*, is the angle between a downward gaze and looking straight ahead; whereas *optical slant*, θ, is the angle between the line of sight and the surface (see figure 5). Li and Durgin (2010) found clear evidence against the intrinsic bias perspective and for a logarithmic effect of viewing distance that they call *angular expansion* (Durgin & Li, 2011; Li & Durgin, 2012). They identify a shortcoming with the intrinsic bias model for hill perception in that the value of bias mentioned here (12.7°) is found in only the dark or nonoptimal viewing conditions when ground-surface information and depth cues are minimal or unreliable (Ooi & He, 2007), and report that, when similar studies are conducted under optimal full-light conditions and fitted with an intrinsic bias model, the error is only 3° (Li & Durgin, 2010).

Li and Durgin (2012) evaluate a direct comparison of the intrinsic bias model and Li and Durgin's (2010) scale expansion model, which states that Ooi et al.'s (2006) model is incapable of accounting for hill slant errors of the magnitude normally observed: in the dark it predicts an error of 12–14°. Furthermore, in full-cue conditions, such as used by our present study, it predicts an error of 2–4° rather than the 20° typically found in full-cue conditions. As we saw with experiment 1, ground-surface texture (paved vs unpaved) was found to influence judged distance (Ooi & He, 2007), where paved hills produced larger errors. The aforementioned studies have all used a variety of surfaces: indoors (Ooi et al., 2006), grassy surfaces (Ooi & He, 2007), virtual reality (Li & Durgin, 2010), paved and unpaved hills (Bridgman & Hoover, 2008), and more.

Although steps were taken by all experimenters in these studies to ensure consistency of judged slopes and application to real-world perception, we contest that it is a stretch to directly compare the findings and results between these studies, given that simply viewing a paved or unpaved hill significantly affects the perception of slant. It appears that more ecologically natural environments produce biases more reminiscent of Ooi et al.'s (2006) findings with less optimal dark room viewing conditions, which differ from those of Durgin and colleagues (Li & Durgin, 2010). In order to test the role of environmental texture, future work in this field must shift from ersatz environments to environments closer to real life. Li and Durgin's angular expansion model, however, comes closer to applying in our full-cue conditions and merits a greater comparison and discussion.

Our findings are consistent with the many other human behaviors that have been found to require the convergence and integration of information communicated through various anatomically discrete sensory pathways (Spence & Driver, 2004). Unfortunately, even now little is known about information processing and integration of human crossmodal perception. Even though there are quite a few examples of perceptual interactions across vision, touch, audition, and linguistic systems, many of the most interesting insights in human crossmodal interactions have emerged only in the last ten years or so (Spence, 2010). This crossmodal integration is consistent with more recent evolutionary models of modularity (see Barrett & Kurzban, 2006, for discussion). Our results, illustrating a continuous instead of discrete interaction between perceived slope of a hill and distance of judged segment from an observer, complement a growing body of research that has recently uncovered the prevalence of multimodal interactions that exhibit a dynamic and continuous perspective of the mind.

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