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Why do Hills Look so Steep?

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Summary

Hills look much steeper than they are. This chapter reviews current knowledge of the phenomenology of slant misperception in relation to both functionalist and mechanistic accounts of this perceptual bias. Recent discoveries suggest that this misperception of the geometry of our environment may be related to useful biological information coding strategies with respect to not only slant, but also other angular variables relevant to the biological measurement of surface layout. Even in the absence of hills, people misperceive the direction of their gaze systematically in ways that seem to contribute to the vertical expansion of the perceived environment.

Key words

Slant, angular declination, surface layout, space perception

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A pervasive illusion in normal human experience is the misperception of surface orientation or slant. An outdoor path that ascends a hill of some 5° is typically judged to be about 20° whether viewed from the top or bottom (Proffitt et al., 1995). Conversely a hill that appears to be about 30° to the casual observer will typically turn out to be between 7° and 10° upon measurement. The magnitude of this error is illustrated in Figure 1. With experience, skiers, hikers, engineers and other frequent viewers of measured hills become aware of this perceptual error and may learn to make more accurate verbal estimates. However, as far as is known, the underlying perceptual bias seems to persist (Durgin & Li, 2011b). In this overview we will consider several different forms of theory that have been proposed for understanding the overestimation of geographical slant in the context of summarizing relevant findings.

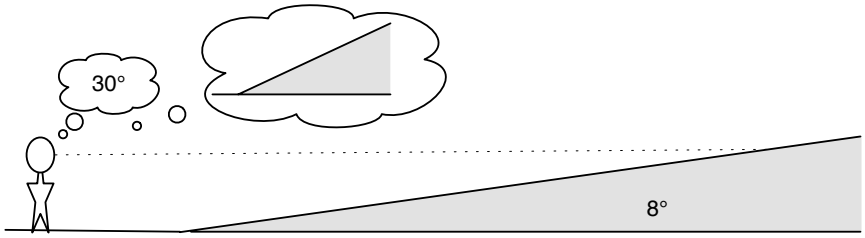


Figure 1. The basic phenomenology: If a hill appears to be nearly 30°, it is probably about 8°. The perceptual error is consistent with foreshortening along the line of sight in the pictured (uphill) case, but downhill slopes also look very steep, which cannot be explained by foreshortening along the line of sight.

To begin with ecological considerations, note that the powerful force of gravity, including both its role in surface erosion and its role in toppling leaning structures, compresses the range of ground orientations with which humans are confronted. This fact is probably quite important to understanding why surface orientation can be systematically overestimated without much cost. The statistical distribution of surface orientations in the environment may, in fact, encourage the expanded coding of surface orientation (Proffitt, 2006; Durgin & Li, 2011b). The second point to be made is that errors in the estimation of surface orientation do not depend exclusively on visual factors. Estimates of underfoot ground orientation while standing on a ramp, for example, show similar patterns of overestimation – even for congenitally blind participants (Hajnal, Abdul-Malak & Durgin, 2011). Indeed, very steep ramps (i.e., 14°) can be judged even steeper under foot (haptically) than when regarded visually (Durgin et al., 2009; Hajnal et al., 2011). Spatial bias in the haptic perception of surface slant has recently been reviewed (Durgin & Li, 2012). The present review will focus on visual slant perception while noting similarities and differences with haptic slant perception. Several of the phenomena discussed here, such as the effect of viewing distance on slant perception are primarily relevant to vision.

Theories of slant overestimation have fallen into the two broad categories of teleological (or *functional*) theories and mechanistic (or *incidental*) theories. Functional theories have focused on several kinds of perceptual or behavioral advantages that might arise from the exaggerated coding or representation of ground orientation. In the natural environment, sensitivity to ground orientation might be used as a basis for recognizing one's facing direction or location in a familiar geographic region (Nardi, Nitsch & Bingman, 2010). It might also be particularly useful for taking energetics into account during route planning (Bhalla & Proffitt, 1999; Proffitt, 2006), and energy costs are highly relevant to coding the vertical dimension of space (Kammann, 1967). Perceptual error might even be used to more efficiently guide motor planning (Hajnal et al., 2011; Li & Durgin, 2012b) or simply to more efficiently represent the layout of the environment (Durgin & Li, 2011b; Durgin, Li & Hajnal, 2010b).

Incidental theories of slant misperception have included the idea that depth along the line of sight is foreshortened (Ross, 1974), which is sufficient to predict that uphill surfaces will appear too steep), or that the perceived horizontal is altered in the presence of hills (O'Shea & Ross, 2007), or that perceptual biases tend to make surfaces appear more frontal than they are (Gibson, 1950). Each of these incidental theories has some measure of support, but none of them seem to fully account for the full range of

observed perceptual biases. The incompleteness of these incidental theories has led some theorists to neglect their importance. But a full account of the overestimation of slant must take these facts into account as well.

The present chapter will argue for a hybrid theory of slant misperception that includes both functional and incidental components. Whereas the exaggeration of the vertical dimension has a clear value for layout recognition and route planning, it may be that a more general perceptual coding advantage supports both of these kinds of goals rather than privileging one or the other. The phenomenology of slant perception is relevant to this discussion.

Constancy and non-constancy in slant perception

Constancy refers to the ability of an organism to perceive one aspect of an object (such as slant) consistently despite irrelevant changes in viewing conditions (such as viewing orientation and optical distance). In this section it will be explained that there are at least two important respects in which the perception of slant is clearly not constant and three important respects in which it is surprisingly constant. In general, purely functionalist theories have limited resources for accounting for the failures of constancy described here, whereas purely incidental theories will often be contraindicated by the presence of constancy.

Effects of viewing distance

As viewing distance from a hill surface increases, the perceived slant of the surface tends to increase (become more vertical), as illustrated in Figure 2. This was demonstrated by Bridgeman and Hoover (2008) by having participants look at different fixation points along a hill of constant slope. At farther distances, perceived slants were greater. This effect is not due simply to a diminution of texture information in the distance or changes in perspective. Even when the direction of gaze is held fixed at horizontal and monocular distance cues are controlled for using high-resolution virtual displays, the perceived orientations of large slanted surfaces (6-36°) increase approximately linearly as a function of log distance (Li & Durgin, 2010). This slope non-constancy with distance can be measured with both explicit verbal estimates of slant and with implicit slant estimates based on judgment of perceived shape on the hill surface. That is, if an L-shaped configuration of balls is simulated on a hill surface and measurement is made of the perceived ratio between frontal and sagittal arms of the L, one can use trigonometry to compute the implied surface orientation relative to the line of gaze. Such computations turn out to be roughly consistent with verbal estimates, helping to confirm that the overestimation of slant is not simply a verbal error.

In the classic hill slant estimation studies of Proffitt et al. (1995), observers were asked to make slant judgments while viewing the hills with gaze forward and standing near the base of the hill. This means that shallow hills would have been observed at a much larger optical distance than steeper hills. For example, assuming an eye-height of 1.6 m, a path of 5° would only reach eye-level 18 m away, whereas, a steep embankment of 33° would reach eye-level within 2.5 m. It was to address this confound that led Li and Durgin (2010) to conduct their study of effects of viewing distance. When viewing distance was kept fixed, the relationship between slant and perceived slant (in the measured range of 0-36°) turned out to be well predicted by assuming that perceived slant increases with a gain of 1.5 relative to physical slant (Li & Durgin, 2010). In fact, a gain of 1.5 is consistent with the first quarter cycle of a sinusoidal function which also seems to approximate the function that relates physical slant to perceived slant for small surfaces in reach (Durgin, Li & Hajnal, 2010; Durgin & Li, 2012). Li and Durgin (2013) have further developed a sine-based model as illustrated in Figure 2.

Panel A of Figure 2 illustrates the principal features of the models developed by Li and Durgin (2010, 2013): At each viewing distance, the perceived slant functions have a gain of approximately 1.5, but the effective intercepts of the functions increase with the log of viewing distance. In this case we have plotted the slant functions for viewing distances associated with each of six of the hills tested by Proffitt et al. (1995), as well as noting the specific slant shown at each distance using the sine-based model of Li and Durgin (2013, Equation 3). Panel B of Figure 2 re-plots these predicted points (and three others)

along with the associated means and standard errors from of Proffitt et al. Although the slant model was developed using virtual displays and implicit slant measurements (judging the aspect ratio of an L-shaped arrangement of balls on a hill surface), it provides an excellent fit to outdoor verbal estimation data.

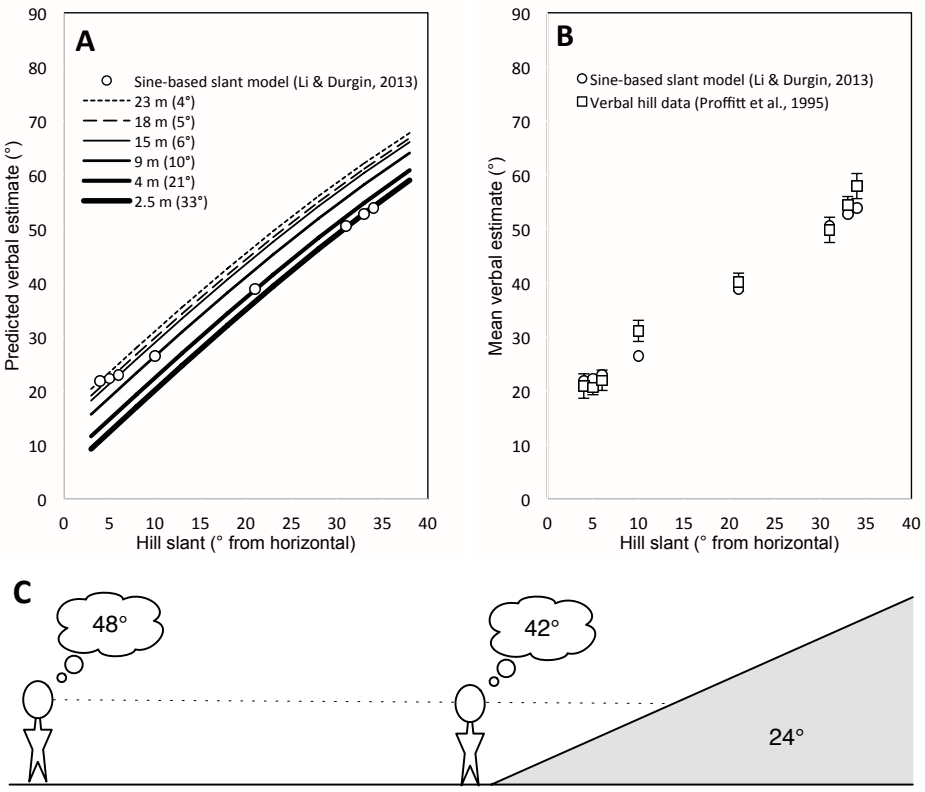


Figure 2. For a farther observer, a hill will appear steeper. A: An illustration of the empirically derived model of the effects of viewing distance on perceived slant (Li & Durgin, 2010, 2013). At each distance slant judgments have a gain of about 1.5 (the function is primarily sinusoidal). B. This one-parameter model fares well at predicting the hill estimation data of Proffitt et al. (1995): Each white circle (in both graphs) represents the model prediction for a specific hill slant taking into account both its slant and the optical distance to hill for an observer at the base of the hill, viewing it with gaze forward. C. The effect of distance generalizes to farther or nearer viewing: a hill of about 24° will be estimated as 42° when standing at the base (with gaze forward, the optical distance to the hill would be about 3.6 m), but as 48° when standing 10 meters back from the base (i.e., 13.6 m from the hill surface at eye-level).

This non-constancy of perceived slant with respect to viewing distance is likely an incidental effect due to a failure of stereoscopic depth scaling. Although textbooks typically discuss binocular disparity as a useful depth cue only for near space, disparity information can be useful out to nearly a kilometer for surfaces that are sufficiently extended in depth (such as hills), but the scaling of stereoscopic depth information is known to show poor constancy at far distances (Palmisano et al. 2010). Many people are aware of the fact that mountains in the distance look essentially vertical. What is harder to notice (though it is observable) is that the apparent slants of hills gradually become shallower as we get closer to them.

If we consider the various functional accounts of hill misperception, it is difficult to see how any of them is strengthened by the effects of viewing distance. Perhaps a landmark could be more readily noted if its slant is exaggerated with distance, but using slant to orient to the environment would seem, on the face of it, to demand more constancy rather than less. Similarly, a functional account in terms of energetics should have trouble accounting for non-constancies. If a climbable slope seems insurmountable

when viewed in the distance, this does not seem particularly useful for route planning. The only functionalist theory that seems to be directly compatible with distance effects (i.e., not contradicted by them) is the expanded coding theory. Coding theory only need imply that slants will be exaggerated to better act upon them. Within immediate action space (several meters), the non-constancies are both minor and fully predictable.

Failures of constancy as optical slant decreases

Li and Durgin (2009) found that downhill slants show a noticeable failure of constancy, depending on viewpoint. Using controls for viewing distance, Li and Durgin reported that downhill slants appeared steepest when the direction of view is nearly parallel to the hill surface, such as when your gaze first crests them. Many skiers have confirmed the basic observation that a downhill slope appears less steep as one gets closer to the edge. Some report that they try to maximize the sense of danger by initiating the process of launching themselves onto the hill before they have fully crested it. The apparent steepening of the hill at the point where gaze is nearly parallel with the surface may serve to signal uncertainty or risk, but it nonetheless appears to be an incidental effect rather than primarily functional because the steepening effect for downhill slants has a corresponding effect for uphill slants: When gaze is nearly parallel to slant, the visual system tends to treat gaze direction itself as the sole estimate of slant (Durgin & Li, 2011b). This effect has been observed for real and simulated downhill surfaces (Li & Durgin, 2009) as well as for small uphill simulated surfaces viewed at shallow optical slants, with gaze nearly parallel to the surface orientation (Durgin & Li, 2011b).

Evidence for constancy with viewing direction

A surprising amount of constancy is evident in slant perception with respect to the lateral direction of gaze. Proffitt, Creem and Zosh (2001) showed that, even when people looked at a hill from an oblique perspective, participants' estimates remained exaggerated. Proffitt et al. did not control for viewing distance, but their data strongly suggest that the encoding of 3D slant provides substantial constancy with respect to direction of observation. For smaller, uphill surfaces, Durgin et al. (2010b) reported an impressive amount of constancy as well with changes in the pitch of gaze, suggesting that coding biases in slant perception affect *geographical* slant (slant relative to gravity) rather than optical slant (slant relative to the line of sight). As shown in Figure 3 (top), Durgin et al., had participants estimate the slants of small surfaces either with gaze forward or with gaze declined by nearly 45°. If slant mis-estimation were due primarily to distance foreshortening along the line of sight (also known as "frontal tendency"), then a board at about 60° from horizontal should seem steeper with gaze forward (Figure 3, top right) than with gaze downward (Figure 3, top left), but no substantial differences were found. The function relating perceived slant to actual slant can be approximated by a sinusoid for slants within arm's reach (Li & Durgin, 2013. This effect is not verbal/numeric: the same spatial bias occurs whether numeric estimates are made relative to vertical or to horizontal. Moreover, when a forced choice procedure was used to measure the bisection point between vertical and horizontal, surfaces of about 34° from horizontal were judged as being 45° (from horizontal and from vertical).

Evidence for constancy across surface size

Although slant illusions are less dramatic for near surfaces at eye level, in the range of slants between 0 and about 50°, perceived orientation is expanded with a gain of about 1.5 (Durgin & Li, 2011b). This same 1.5 gain function is evident in the models of large-scale slants discussed above. That is, the perceived orientation of small real surfaces presented under full-cue conditions are expanded in the lower half of the range by a factor of about 1.5, and exactly the same scaling factor applies to large scale hills. Thus, the perceived orientation of large-scale surfaces seems to be no different, with respect to bias, than the perceived orientation of smaller-scale surfaces. The success of the sine-based model in capturing both the hill data and the data from small surfaces shows that there no discontinuity between small and large surfaces in slant misperception (Li & Durgin, 2013). This point, again, is consistent with the expanded coding theory because it points to a generalized coding scheme that applies to slant in general rather than exclusively to landmarks or to intended paths of travel.

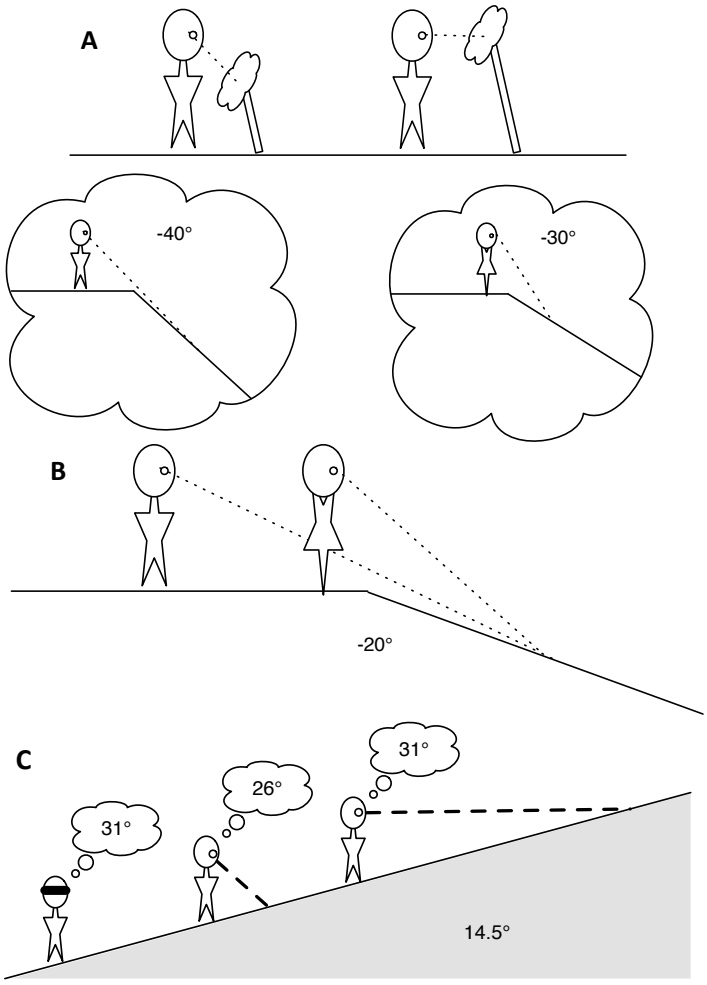


Figure 3. A. In near space, the same estimation function is found for slant whether surfaces are viewed with gaze downward or with gaze forward (Durgin et al., 2010b). B. Hills look steeper when standing back from the edge so that gaze is nearly parallel to the surface of the hill. When optical slant (the angle between the center of gaze and the surface) is small, surface orientation is pulled toward the direction of gaze (Li & Durgin, 2009; Durgin & Li, 2011b). The angular declination of gaze is, itself, exaggerated (independent of the presence of the hill), which helps to account for the overestimation even at the edge. C. For steep ramps, estimates given when blindfolded (haptic) more closely resemble visual estimates when gaze is forward (even when the head is bowed – Hajnal et al., 2011), than visual estimates when a nearer portion of the ramp is inspected.

Evidence for constancy across modalities

As reviewed by us elsewhere, a sine-based model can apply to haptic surface perception by hand as well (Durgin & Li, 2012) and even to proprioception of hand orientation (Li & Durgin, 2012b). Thus, the underlying spatial bias function in slant perception seems to be multimodal. Even in the cases that seem exceptional, further analysis suggests good calibration between modalities. For example, Durgin et al. (2009) reported that verbal estimates of a 14.5° ramp were only 26° when based on visual inspection of the ramp while standing near the base (and looking down), whereas estimates from haptic information while standing on the ramp were closer to 31°. The second (haptic) estimate corresponds well with the sine-based model estimate of visually perceived slant for a 14.5° hill when viewed with gaze forward from the base (with a viewing distance to surface of about 6.5 m). In other words, if a person were walking up such a hill and simultaneously viewing the hill with gaze forward, the visual perception of

slant and the haptic perception would be aligned (both would be about 31°). In contrast, the 26° estimate can be arrived at by using the actual viewing distance to the ramp surface (about 2 m) in the model.

Summary of slant constancy

The evidence we have reviewed here suggests that perceived slant shows marked failures of constancy with viewing distance and with certain extreme directions of gaze with respect to surface orientation. In contrast, visually perceived slant is remarkably constant across most changes in viewing orientation, across different scales of surface size (when viewing distance is taken into account) and across different modalities. Perhaps the most significant fact about the systematic biases in slant perception is that these biases seem to be coded primarily with respect to the extrinsic reference frame specified by gravity (Durgin et al., 2010b) though some incidental effects indicate that there are also consistent biases with respect to optical slant as well.

Socio-cognitive factors in the evaluation of slant

A number of reports have been made suggesting that slants looks steeper to people for whom they represent a greater challenge to scale. A list of factors that have been said to affect the evaluation of slant include age, fitness, encumberment, fatigue (Bhalla & Proffitt, 1999), fear (Stefanucci, Proffitt, Clore & Parekh, 2008), social support (Schnall, Harber, Stefanucci & Proffitt, 2008) and blood sugar (Schnall, Zadra & Proffitt, 2010). These various studies have been critiqued extensively (Durgin et al., 2009; Durgin, Hajnal, Li, Tonge & Stigliani, 2010a, 2011; Durgin, Klein, Spiegel, Strawser & Williams, 2012a; Durgin, Ruff & Russell, 2012b; Shaffer, McManama, Swank & Durgin, 2013). In some cases, such as a study of the elderly, the originally published data actually contradicted the hypothesis: The elderly gave lower estimates for most hills, but this was not made evident in the initial report. In other cases, such as a study of fitness, confounding factors (e.g., sex differences in slant estimation) were not taken into account in the analyses (see Durgin et al., 2010a for a discussion). In yet others concerned with fear, subjects may have been excluded from analysis in a manner that inadvertently biased the results (see Durgin et al., 2009, for a discussion).

The critiques of the studies of encumberment are worth reviewing briefly here. If participants in a study are simply asked to wear a heavy backpack, they tend to give higher estimates for hills than do non-encumbered participants. However, they also tend to report that they thought the backpack was supposed to make the hill look steeper (Durgin et al., 2009; Durgin et al., 2012a). If the backpack is instead presented as carrying equipment essential to the conduct of the experiment (Durgin et al., 2009; Durgin et al., 2012b; Shaffer et al., 2013), or participants are told not to let themselves be influenced by the backpack (Durgin et al., 2012a), the judgments that they give tend to be identical to those of non-encumbered participants. In general, the use of heavy backpacks that are transparently intended to increase estimates of slant seem to produce social pressure on participants to elevate their slant estimates. Susceptibility to that social pressure can be mitigated by social support (Schnall et al., 2008), and may be exacerbated by low blood sugar (Durgin et al., 2012a; Schnall et al., 2010; Shaffer et al., 2013). Durgin et al. 2012a found that the effects of blood sugar disappeared when participants were simply told to ignore the heavy backpack they were required to wear during such studies. Shaffer et al. (2013) showed that low blood sugar produces opposite effects (lower estimates) if participants believe the drink (which they assume contained sugar) was supposed to make the hill look shallower. Disputes over these sorts of controversial findings remain lively in the current literature. It is very clear that social compliance can have powerful effects on judgments and should be controlled for in studies of perception.

The idea that slant overestimation provides a means for the direct perception of the energetic affordances of the environment (Proffitt, 2006) is quite a clever one. However, much of the evidence amassed in support of this theory has proven problematic, and no direct connection seems to exist between energetics and slant perception (e.g., Shaffer & Flint, 2011). A surviving tenet of this view, however, is that geometric accuracy might not be the proper goal of perceptual representation. This is also a tenet of expanded scaling theory, and if the exaggeration of perceived slant incidentally helps people to

more reliably evaluate the energetic affordances of the environment for the purpose of route planning, so much the better.

The role of the perceived direction of gaze

Because slant is defined relative to a gravitational reference frame (i.e., the horizontal plane and the vertical vector of gravity that is normal to horizontal), errors in perceived slant could come about if the presence of a hill produced a distortion in the perception of the horizontal plane. O'Shea and Ross (2009) have provided evidence for such effects in the presence of large scale mountains (see also Matin & Li, 1992), and Ooi and He (2007) have suggested that the ground plane itself is perceived as being tilted upward. The magnitude of such effects, however (about 3-5°), is insufficient to account for the very large magnitudes of distortion in perceived slant.

Recently a much more dramatic distortion in perceived gaze direction has been documented which seems more consistent with the overestimation of slant. Specifically, much as the perceptual gain for perceived slants (less than 45°) is about 1.5 when distance is fixed, Li and Durgin (2009; Durgin & Li, 2011b) have used a variety of methods to document that the perceived declination of gaze is also coded with a gain of about 1.5. Durgin and Li (2011b; Li & Durgin, 2012a) have proposed that angular variables relevant to the pitch axis are coded on an expanded scale so as to increase their precision because they are highly relevant for action.

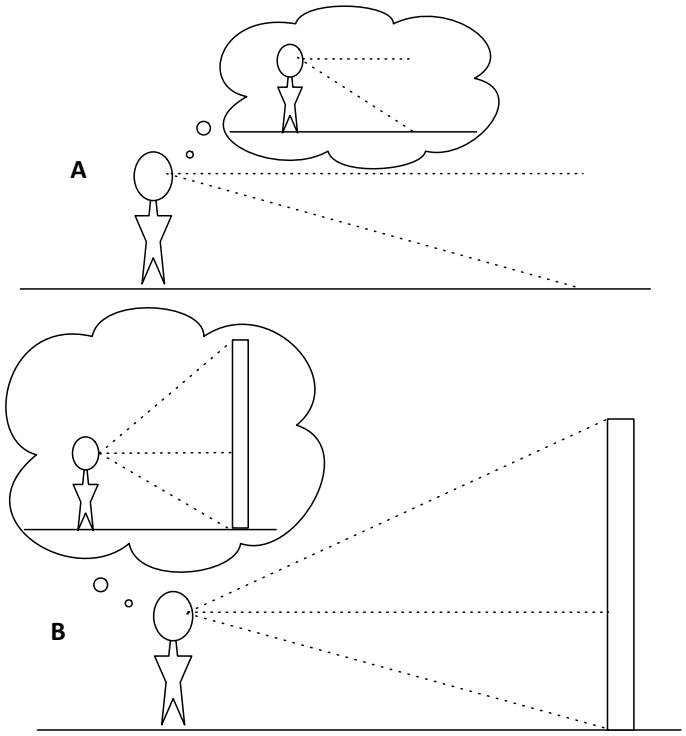


Figure 4. A. Independent of the presence of a ground surface, perceived gaze declination (within 45° of horizontal) is exaggerated by a gain of 1.5 (Li & Durgin, 2009; Durgin & Li, 2011b). B. Asked to set themselves the same distance from a pole as the pole is high, participants set themselves much too far away (Higashiyama & Ueyama, 1988). The mismatch between their perceptual experience and the physical situation can be predicted by the scaling of the perceived angular declination of gaze (Li et al., 2011).

Gaze declination relative to the horizon is a powerful cue to distance (Wallach & O'Leary, 1982; Sedgwick, 1986; Ooi, Wu & He; 2001, Messing & Durgin, 2005), because on level ground (and most of the spaces we deal with are within 5° of level) it provides highly reliable proprioceptive cue to ground distance. Given the bandwidth limitations of neural transmission, coding this angular variable on an expanded scale would preserve greater precision relevant for the control of action. Thus a functional

account of slant overestimation derives in part from the idea that angular distortions are present in perceptual experience in order to maintain precision for action. The expanded scaling of perceived gaze declination has been measured implicitly (Li & Durgin, 2009; Durgin & Li, 2011b) based on slant estimates viewed along different lines of sight; it has been measured directly with balls suspended in the air or placed along the ground, and it has been measured by means of a bisection task (Durgin & Li, 2011b; see also Durgin & Li, 2011a). In all cases the gain was found to be approximately 1.5. Studies of verbal distance estimation among non-experts tend to suggest linear compression of perceived ground distance by a factor of 0.7-0.8 (Loomis & Philbeck, 2008), consistent with a misperception of gaze direction, as illustrated in Figure 4 (top). Rather than hills looking steep because of distance foreshortening, it may be that ground distances are underestimated because crucial angular variables, such as the angle of gaze declination, are systematically misperceived.

Strikingly, this expanded scaling of perceived angular declination of gaze (along with a concomitant scaling of optical slant) can predict not only downhill slant perception (Li & Durgin, 2009; see Figure 3, bottom), but also systematic errors in the comparison of distance and height. For example, Higashiyama and Ueyama (1988) developed a task requiring participants to place themselves at the same distance from objects (such as poles) as those objects were high. Participants placed themselves much too far away, as illustrated in Figure 4 (bottom). Li, Phillips and Durgin (2011) recently replicated this experiment and extended it to show that the exact pattern of results reported by Higashiyama and Ueyama could be predicted by a parameter-free geometric model in which the previously measured angular declination gain of 1.5 was assumed. This suggests that hill misperception is part of a larger pattern of angular distortions that affect the perception of surface layout generally.

Why then do hills look so steep?

Slant misperception is dramatic. An editor at a journal once challenged the statement that Lombard Street in San Francisco is on a hill that is only 15° in slope. He said he had checked the internet and found that the true value is 31°. He was correct that many sites on the internet report a value of 31°. In fact, the tangent of 15° is 0.31 and so the grade of the hill is 31% (a 100% grade would be a 45° slope). Since 15° is simply unbelievable for anyone who has been to Lombard Street, many web sites simply report this as 31° (which still seems too low compared to the perceptual phenomenology). The hill is so steep that Lombard Street winds back and forth across it so as to reduce the effective slant of the road to 10° -- still quite steep for behavior!

As Marr (1982) pointed out, there are many different forms of answer to questions about explanation including the functional and the mechanistic. This chapter has considered the phenomenology of hill perception while discussing a variety of theories that have been proposed. One answer to the question in the title might remain the one proposed by Kamman (1967): Because of gravity. The environment in which we have evolved is laid out such that vertical extents and slants are relatively tiny compared to horizontal extents. Expanding the vertical scaling of such an environment might produce many cognitive advantages, even if that expansion is done in angular terms. A second, mechanistic, answer remains: Because of a loss of reliable information for depth along the line of sight. This latter answer addresses the failure of slant constancy with changes in viewing distance, but it cannot be the whole story, because it does not account for the misperception of downhill slant nor the relative constancy of perceived slant with large changes in angle of regard. This chapter has emphasized that the misperception of hills is probably part of a larger family of biases in the perception of angular variables that includes the misperception of small surfaces in reach and may even include the misperception of ground distance and height based on multiplicative biases in perceived angular deviations of visual direction from horizontal.

Although this review has taken sides on some controversies, there was not room to address recent controversies over the interpretation of different measurement techniques for evaluating perceived slant (e.g., Coleman & Durgin, in press; Creem & Proffitt, 1998; Durgin, 2013; Durgin et al., 2010a, 2010b; Li & Durgin, 2010, 2011, 2013; Stigliani, Li & Durgin, in press; Taylor-Covill & Eves, 2013; Witt &

Proffitt, 2007). These controversies focus around the question of whether using a haptic matching task to measure slant provides a route to a separate (undistorted) dorsal stream representation.

It is therefore worth making one final point about the non-consequences of slant misperception. Our actions seem to be coded in the same perceptual space as everything else (Powers, 1973). This means that acting with accuracy in a perceptually distorted world only requires that actions be calibrated to the same distortions (Durgin, 2009). For example because proprioception of hand orientation is distorted with precisely the same function as the haptic and visual perception of surfaces (Li & Durgin, 2012b), the perceptual distortions documented here are transparent to our action systems. We can live and act effectively in a distorted visual world. Because the distortion is fairly stable, and the correlations between motor signals and sensory signals are maintained, even the effects of non-constancy with distance can be predicted and therefore ignored in our normal perceptual experience. An important part of the answer to why hills (and even small surfaces in reach) look so steep is therefore: Why not?

Literature cited

Bhalla, M., & Proffitt, D. R. (1999). Visual-motor recalibration in geographical slant perception. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1076– 1096.

Coleman, A., & Durgin, F. H. (in press). Egocentric reference frame bias in the palmar haptic perception of surface orientation. *Psychonomic Bulletin & Review*.

Creem, S. H., & Proffitt, D. R. (1998). Two memories for geographical slant: Separation and interdependence of action and awareness. *Psychonomic Bulletin and Review, 5*, 22–36.

Durgin, F. H. (2009). When walking makes perception better. *Current Directions in Psychological Science, 18*, 43-47.

Durgin, F. H. (2013). What do hands know about hills? Interpreting Taylor-Covill and Eves (2013) in context. *Acta Psychologica, 144*, 451-458.

Durgin, F. H., Baird, J. A., Greenburg, M., Russell, R., Shaughnessy, K., & Waymouth, S. (2009). Who is being deceived? The experimental demands of wearing a backpack. *Psychonomic Bulletin & Review, 16*, 964-969.

Durgin, F. H. Hajnal, A., Li, Z., Tonge, N., & Stigliani, A. (2010a). Palm boards are not action measures: An alternative to the two-systems theory of geographical slant perception. *Acta Psychologica, 134*, 182-197. http://dx.doi.org/10.1016/j.actpsy.2010.01.009

Durgin, F. H. Hajnal, A., Li, Z., Tonge, N., & Stigliani, A. (2011). An imputed dissociation might be an artifact: Further evidence for the generalizability of the observations of Durgin et al. 2010. *Acta Psychologica, 138*, 281-284. http://dx.doi.org/10.1016/j.actpsy.2010.09.002

Durgin, F. H., Klein, B., Spiegel, A., Strawser, C. J., & Williams, M. (2012a). The social psychology of perception experiments: Hills, backpacks, glucose and the problem of generalizability. *Journal of Experimental Psychology: Human Perception and Performance 38*, 1582-1595.

Durgin, F. H., & Li, Z. (2011a). The perception of 2D orientation is categorically biased. *Journal of Vision, 11(8):13*, 1-10.

Durgin, F. H., & Li, Z. (2011b). Perceptual scale expansion: An efficient angular coding strategy for locomotor space. *Attention, Perception & Psychophysics, 73*, 1856-1870. doi: 10.3758/s13414-011-0143-5

Durgin, F. H., & Li, Z. (2012). Spatial biases and the haptic experience of surface orientation. In A. El Saddik (ed.), *Haptics Rendering and Applications* (pp. 75-94), Intech.

Durgin, F. H., Li, Z., & Hajnal, A. (2010b). Slant perception in near space is categorically biased: Evidence for a vertical tendency. *Attention, Perception & Psychophysics, 72*, 1875-1889.

Durgin, F. H., Ruff, A. J., & Russell, R. (2012b). Constant enough: On the kinds of perceptual constancy worth having. In G. Hatfield and S. Allred (eds.), *Visual Experience: Sensation, Cognition and Constancy* (pp. 87-102). Oxford University Press.

Gibson, J. J. (1950). The perception of visual surfaces. *American Journal of Psychology, 63*, 367–384.

Hajnal, A., Abdul-Malak, D. T., & Durgin, F. H. (2011). The perceptual experience of slope by foot and by finger. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 709-719.

Higashiyama, A., & Ueyama, E. (1988). The perception of vertical and horizontal distances in outdoor settings. *Perception & Psychophysics, 44,* 151–156. DOI:10.3758/BF03208707

Kammann, R. (1967). Overestimation of vertical distance and slope and its role in the moon illusion. *Perception & Psychophysics, 2*, 585–589.

Li, Z., & Durgin, F. H. (2009). Downhill slopes look shallower from the edge. *Journal of Vision, 9(11):6*, 1-15.

Li, Z. & Durgin, F. H. (2010). Perceived slant of binocularly viewed large-scale surfaces: A common model from explicit and implicit measures. *Journal of Vision, 10(14):13*, 1-16.

Li, Z., & Durgin, F. H. (2011). Design, data and theory regarding a digital hand inclinometer: A portable device for studying slant perception. *Behavior Research Methods, 43*, 363-371.

Li, Z., & Durgin, F. H. (2012a). A comparison of two theories of perceived distance on the ground plane: The angular expansion hypothesis and the intrinsic bias hypothesis. *i-Perception, 3*, 368-383.

Li, Z., & Durgin, F. H. (2012b). Manual matching of perceived surface orientation is affected by arm posture: Evidence of calibration between proprioception and visual experience in near space. *Experimental Brain Research, 216*, 299-309. DOI: 10.1007/s00221-011-2934-2

Li, Z., & Durgin, F. H. (2013). Depth compression based on mis-scaling of binocular disparity may contribute to angular expansion in perceived optical slant. *Journal of Vision, 13(12):3*, 1–18. DOI: 10.1167/13.12.3

Li, Z., Phillips, J., & Durgin, F. H. (2011). The underestimation of egocentric distance: Evidence from frontal matching tasks. *Attention, Perception & Psychophysics, 73*, 2205-2217. doi: 10.3758/s13414-011-0170-2

Loomis, J. M., & Philbeck, J. W. (2008). Measuring spatial perception with spatial updating and action. In R. L. Klatzsky, B. MacWhinney, and M. Behrmann (eds), *Embodiment, Ego-space, and Action* (pp 1-43), New York: Taylor and Francis.

Marr, D. (1982). *Vision*. New York: Freeman.

Matin, L., & Li, W. (1992). Visually perceived eye level: Changes induced by a pitched-from-vertical 2-line visual field. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 257-289.

Nardi, D., Nitsch, K. P., & Bingman, V. P. (2010). Slope-driven goal location behavior in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, 36, 430-442.

Ooi, T. L., Wu, B., & He, Z. J. (2001). Distance determined by the angular declination below the horizon. *Nature, 414*, 197–200.

Ooi, T. L., & He, Z. J. (2007). A distance judgment function based on space perception mechanisms: Revisiting Gilinsky's (1951) equation. *Psychological Review, 114*, 441–454.

O'Shea, R. P., & Ross, H. E. (2007). Judgments of visually perceived eye level (VPEL) in outdoor scenes: Effects of slope and height. *Perception, 36*, 1168–1178.

Palmisano, S., Gillam, B., Govan, D. G., Allison, R. S., & Harris, J. M. (2010). Stereoscopic perception of real depths at large distances. *Journal of Vision, 10(6): 19. doi:10.1167/10.6.19*

Powers, W. T. (1973). *Behavior: The control of perception.* Chicago: Aldine.

Proffitt, D.R. (2006). Embodied perception and the economy of action. *Perspectives on Psychological Science,* 1, 110-122.

Proffitt, D.R., Bhalla, M., Gossweiler, R., & Midgett, J. (1995). Perceiving geographical slant. *Psychonomic Bulletin & Review,* 2, 409-428.

Proffitt, D. R., Creem, S., & Zosh, W. (2001). Seeing mountains in molehills: Geographical slant perception. *Psychological Science, 12*, 418-423.

Ross, H. E. (1974). *Behavior and perception in strange environments.* London: George Allen & Unwin.

Schnall, S., Harber, K. D., Stefanucci, J., & Proffitt, D. R. (2008). Social support and the perception of geographical slant. *Journal of Experimental Social Psychology, 44,* 1246-1255.

Schnall, S., Zadra, J. R., & Proffitt, D. R. (2010). Direct evidence for the economy of action: Glucose and the perception of geographical slant. *Perception, 39,* 464−482.

Sedgwick, H. A. (1986). Space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.). *Handbook of perception and human performance* (pp. 21.1–21.57). New York: John Wiley.

Shaffer, D. M., & Flint, M. (2011). Escalating slant: Increasing physiological potential does not reduce slant overestimates. *Psychological Science, 22,* 209-211.

Shaffer, D. M., McManama, E., Swank, C., & Durgin, F. H. (2013). Sugar and space? Not the case: Effects of low blood glucose on slant estimation are mediated by beliefs. *i-Perception, 4*, 147-155.

Stefanucci, J. K., Proffitt, D. R., Clore, G. L., & Parekh, N. (2008). Skating down a steeper slope: Fear influences the perception of geographical slant. *Perception, 37*, 321–323.

Stigliani, A., Li, Z., & Durgin, F. H. (in press). Humans have precise knowledge of familiar geographical slants. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Taylor-Covill, G. A. H., & Eves, F. F. (2013). The accuracy of 'haptically' measured geographical slant perception, *Acta Psychologica, 144*, 444-450.

Wallach, H. & O'Leary, A. (1982). Slope of regard as a distance cue. Perception & Psychophysics, 31, 145-148.

Witt, J. K., & Proffitt, D. R. (2007). Perceived slant: A dissociation between perception and action. *Perception, 36*, 248-257.