ANGULAR OVERESTIMATION ENHANCES CODING PRECISION: SCALE EXPANSION THEORY IN SLANT PERCEPTION

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Abstract

Why do hills appear so much steeper than their physical orientation? We review recent evidence for three distinct theories of slant overestimation including effort theory, depth foreshortening theory, and a new proposal, scale expansion theory. Scale expansion theory can account for a variety of errors in the perception of orientation across visual and haptic modalities, as well as the proprioception of gaze declination – an important variable in the perception of both slant and distance. Scale expansion theory proposes that angular scaling exaggerates deviations from defaults (such as horizontal) for the sake of precise coding. The theory is supported by explicit measures (including numeric measures and angle bisection tasks) as well as by implicit measures of perceived optical slant based on judging the aspect ratio of an L presented on a slanted surface. The misperception of hills can be understood as resulting from a combination of expansion of angular scales in near space and an increase of perceived optical slant with log viewing distance.

Hills appear much steeper to us than their true slant. It has long been argued that this is true of visually-perceived hills (e.g., Kammann, 1967; Ross, 1974). Recently it has been observed that the haptically-perceived surface orientation under our feet is similarly overestimated – even in the congenitally blind (Hajnal, Abdul-Malak & Durgin, in press). In this paper we will present our scale-expansion theory of hill perception and provide an overview of how that theory accounts for existing data. We first consider the explanatory power of two prior theories.

Three theories of slant overestimation

Three major forms of theory have been proposed to account for the visual misperception of slant. Kammann (1967) proposed that the misperception of slant had to do with the greater physical effort associated with the vertical axis of space. This view was revived by Proffitt et al. (1995) as the *effort hypothesis*; it suggests that perception reflects our behavioral potential. Although many findings have been described in support of the effort hypothesis, methodological critiques and failures to replicate have rendered it controversial. People do judge slants as steeper when asked to wear a heavy backpack during an experiment, but only if they think that that is what the researcher intended them to do (Durgin, Baird et al., 2009; Durgin, Ruff & Russell, in press). Kammann, himself, rejected the effort hypothesis. Although the effort hypothesis seems to be compatible with haptic misperception of ramps underfoot, Durgin, Baird et al.'s study of *demand characteristics* used haptically and visually-perceived ramps and found no evidence in support of the effort hypothesis. In other words, the effort hypothesis has adequate *theoretical* generalizability, but the empirical evidence that had seemed to support it is quite tenuous (see Durgin, Hajnal et al., 2010, in press).

The second form of theory regarding the exaggerated misperception of hills is that slant error results from *depth foreshortening* that increases with increasing viewing distance. This is a proposal put forward by Ross (1974, 2010). It is well known that farther extents along the ground appear increasingly compressed. If the geometry of space includes a compressive non-linearity, this predicts that, for example, farther slanted surfaces will appear steeper than near slanted surfaces of the same physical orientation, and this conjecture has been supported by a number of studies (Bridgeman & Hoover, 2008; Ross, 2010). The idea that slant perception is derivative from the ratio of horizontal to vertical extent provides a fairly good qualitative account of these findings of increasing slant with increasing distance for uphill slants (and decreasing slant for downhill surfaces -- Ross, 2010). But it does not provide a general account of (1) why slanted surfaces underfoot feel so steep (even to the congenitally blind) and (2) why downhill surfaces ever appear steeper than they are. Although O'Shea and Ross (2007) have shown that people standing in front of hills also make errors in judging the horizontal, and Ooi, Wu and He (2006) have suggested that flat ground surfaces are themselves misperceived as slanted upward (perhaps also indicating an error in perceiving the true horizontal), neither of these observations seems to provide a coherent account of why downhill slants also appear steeper than they are.

A partial solution to the downhill slant problem was recently proposed by Li and Durgin (2009). They found that that the perceived deviation of gaze from horizontal is exaggerated in normal observers by a factor of about 1.5. Thus, when looking down a hill, one experiences the slant of the hill relative to a highly distorted egocentric frame of reference. For example, if looking down by 30° at a 20° downhill slant, even if one overestimated the surface orientation relative to one's line of sight (e.g., as 15° instead of 10°), one would overestimate its downhill slant as being about 30° because one would feel that one's gaze was declined by 45° (45°-15° = 30°). Because the exaggeration of perceived declination of gaze seems to be another example of slant overestimation, Li and Durgin proposed a third view of slant exaggeration

This third view of slant misperception, *scale expansion* theory, supposes that angular variables are very important for motor control because they provide an egocentric metric of where things are in space, and that pervasive exaggerated coding of angular variables might help overcome transmission noise when communicating with the motor planning systems. That is, by encoding angles in terms of exaggerated deviations from expected values, one achieves efficient coding of the range of angles normally encountered, and this may explain both why the perceived direction of gaze declination is exaggerated with a gain of 1.5 and why the slants of hills are overestimated.

Evidence for Expanded Scaling of Surface Orientation

Durgin, Li and Hajnal (in press) carefully measured the perceived orientation of small wooden surfaces within reach for which actions (reaching) were quite accurate (Durgin, Hajnal et al., 2010). They found strong evidence that the perceived angular deviations of surfaces from vertical were underestimated and that deviations from horizontal were overestimated in numeric estimates whether vertical was described as being 0° or as being 90°. Even in a non-numeric task, the physical orientation that was (psychometrically) judged to be equidistant between vertical and horizontal in a forced-choice procedure was only 34° from horizontal. Durgin et al. showed that these angular biases were not attributable to "frontal tendency", as described by Gibson (1950), because the same bias was found whether the boards were at eye-level, with gaze forward, or positioned somewhat lower so that gaze was declined by about 40° when looking at the surfaces. Fig. 1 (left panel) shows that verbal estimates of 45° were given for a surface 34° from horizontal (or about 54° from vertical).

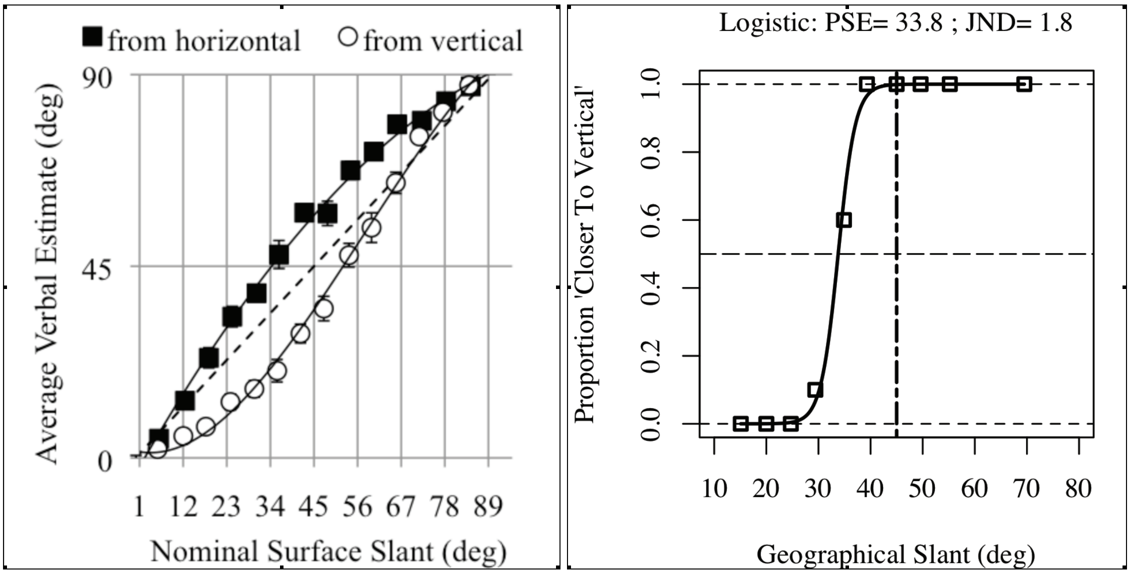

Fig. 1. Evidence from two explicit methods of measuring perceived slant: verbal report (left) and apparent bisection point (right). Data are for full-cue wooden surfaces presented at chest level about 50 cm from the observer (from Durgin, Li & Hajnal, in press). By both methods it appears that a slant of about 34° from horizontal is perceived as being 45°.

Fig. 1 (right) shows a sample psychometric function indicating that a similar orientation (33.8° from horizontal) was judged equidistant from vertical and horizontal.

Evidence for Expanded Scaling of Gaze Declination

If one considers only surfaces between about 4° and 48° from horizontal, numeric slant estimates appear to vary linearly with a gain of almost exactly 1.5. This has proven true across a variety of studies we have carried out with real surfaces in near space (from 0.5 m to 2.5 m). Notice that the exaggerated scaling of perceived gaze declination demonstrates exactly the same pattern: a nearly linear exaggeration with a gain of 1.5 for gaze declinations less than about 50° from horizontal (Li & Durgin, 2009; Durgin & Li, 2010), as shown in Fig. 2. Again, these are not simply verbal biases: a vertical/horizontal bisection task for perceived gaze declination found a perceived midpoint of about 32° (Durgin & Li, 2010).

Of course, the range of the expanded scale is limited so that angular estimates do not "overflow" the range of possible angles (0-90). There is compression of perceived slants within about 30° of vertical. However, the range of 0-45° from horizontal is an important (and sufficient) input range for most purposes. For example, during normal walking, downward glances typically look ahead on the ground by at least a couple of steps (Marigold & Patla, 2006), and usually more, with the result that gaze is rarely declined more than 45°.

An important predicted consequence of the scale-expansion of perceived gaze declination is the underestimation of ground distance. That is, if people feel that they are looking down by 45°, when they are actually only looking down by 34°, then (assuming they correctly perceive their eye-height), they ought to underestimate egocentric distance by a factor of 0.67. In fact, reports of explicit egocentric distance estimates are often distorted by a similar factor (e.g., Foley, Ribeiro-Filho & Da Silva, 2004). In other words, the misperception of gaze declination (which can be measured in the absence of a ground surface) appears to predict the commonly observed finding of egocentric distance underestimation.

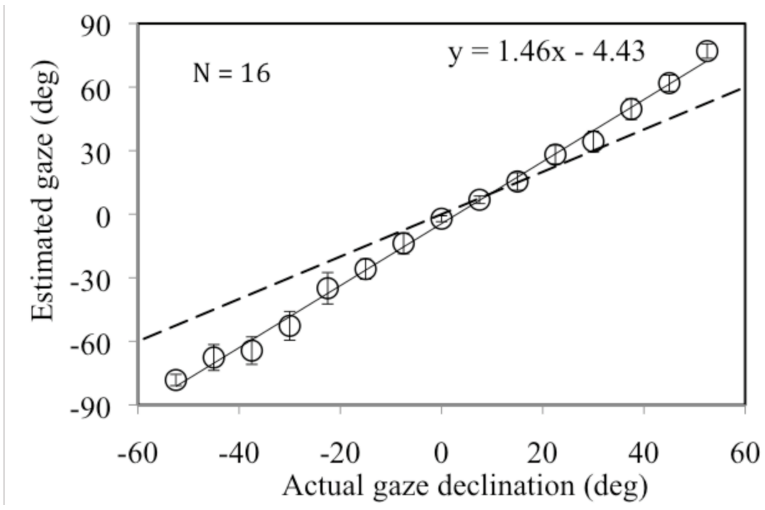

Fig. 2. Sample perceived gaze declination data (negative for elevated gaze) shows approximately the same (1.5) gain seen in surface perception. Data are from study conducted in immersive virtual reality (Durgin & Li, 2010).

A majority of the locomotor surfaces we interact with are within about 5° of horizontal. Thus, in most circumstances, our true gaze declination angle differs by less than 5° from the *optical slant* between our gaze and the ground. This means that the exaggerated scaling of both *optical slant* (surface orientation relative to gaze) and perceived declination of gaze (i.e., relative to horizontal) will tend to cancel out for horizontal surfaces but will exaggerate both uphill and downhill slants of surfaces that are not horizontal.

Effects of Distance on Slant Exaggeration

Scale expansion theory predicts relatively small errors in slant perception (by a factor of 1.5), but large-scale hills of as little as 5° are routinely described by research participants as 20°. How can this magnitude of error be accounted for? In the first place, it is important to note that there is a growing body of evidence suggesting that perceived slant increases with increased viewing distance (e.g., Bridgeman & Hoover, 2008; Ross, 1974, 2010). Although a near surface of 5° might indeed appear to be about 7.5°, a hill of 5° viewed with gaze forward is 18 m away for an individual with an eye-height of 1.6 m, standing at its base.

To measure effects of distance on slant perception, Li and Durgin (2010) used a high-fidelity immersive virtual environment (optically-corrected and calibrated) to present large-scale stereoscopic textured surfaces at eye-level. They independently varied the viewing distance to the surfaces and the orientations of the surfaces. Verbal estimates of surface orientation (relative to gaze) were collected for each distinct combination of slant and distance. In a second experiment, aspect ratio judgments were collected for L-shaped configurations of balls on the surfaces of distinct combinations of slant and distance.

The aspect ratio task is an implicit optical slant task. Based on the retinal ratio between sagittal and frontal extents at apparent equality, one can deduce the perceived surface orientation (relative to gaze) based on the inverse sine of the retinal size ratio.

Fig. 3 shows that both the explicit (left) and the implicit (right) slant estimates can be modeled in the same way: At each viewing distance, the slant gain is about 1.5, but between viewing distances, there is an intercept shift in the slant function that increases roughly linearly with the log of distance (see Bridgeman & Hoover, 2008). Fig. 4 shows predicted slant perception, based on models of Fig. 3 data, compared to verbal hill estimation data from

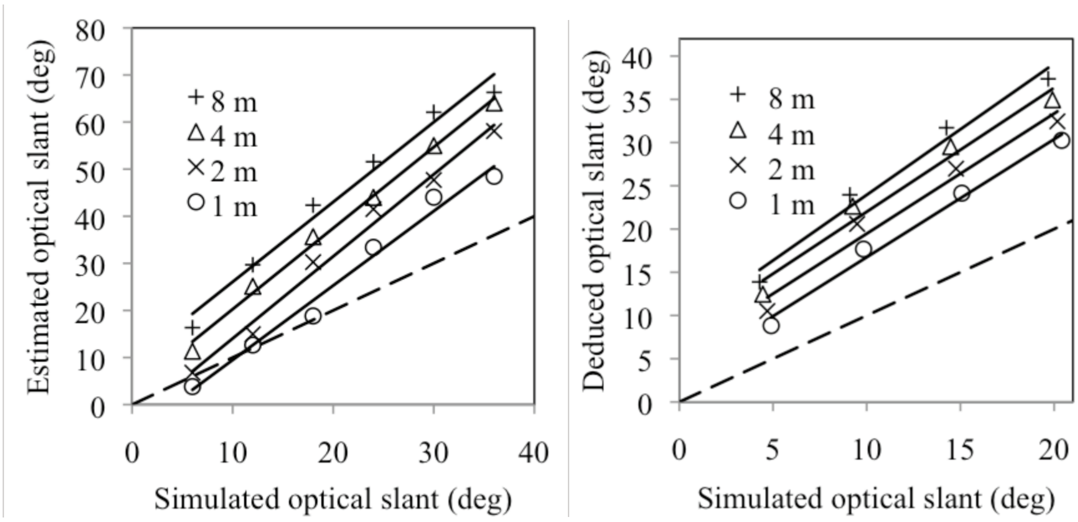

Fig. 3. Effects of viewing distance on explicit slant estimates (left) and implicit slant estimates (right). Slant gains are about 1.5 at each viewing distance.

Proffitt et al. (1995). The models, with a constant slant gain of about 1.5 and an increasing intercept proportional to log viewing distance, provide excellent matches to existing slant estimation data in which viewing distance and surface orientation were confounded.

We emphasize that the effects of viewing distance are not a prediction of scale-expansion theory. However, the fact that a slant gain of about 1.5 is found at each viewing distance supports the idea that angular variables are indeed coded on an expanded scale, while additional slant distortions (with respect to optical slant) can occur as a consequence of increases in viewing distance (see Li & Durgin, 2010, for discussion).

Conclusion

The present data are consistent with the idea that some *exocentric* distance compression errors result from misperception of optical slant rather than the other way around, and that *egocentric* distance errors may result from misperception of gaze declination. We propose that expanded perceptual scaling is a functional coding strategy for the control of action in near space. Gaze declination and optical slant are both important variables for the control of locomotion. Both appear to be represented on expanded scales even when non-verbal methods (like the aspect ratio task and angle bisection task) are used to assess them.

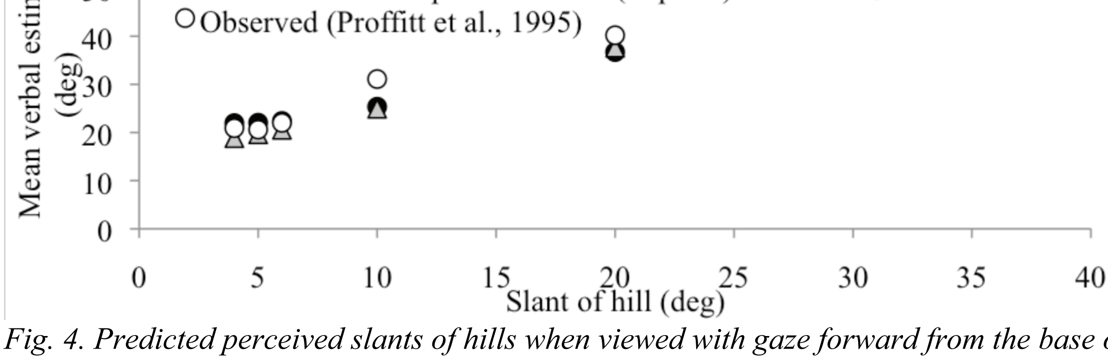

Fig. 4. Predicted perceived slants of hills when viewed with gaze forward from the base of the hill (Li & Durgin, 2010) alongside data of Proffitt et al. (1995).

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