Journal of Vision (2009) 9(12):8, 1–11 http://journalofvision.org/9/12/8/

Stereoscopic discrimination of the layout of ground surfaces

Robert S. Allison Centre for Vision Research, York University, Canada

Barbara J. Gillam School of Psychology, University of New South Wales, Australia

Stephen A. Palmisano School of Psychology, University of Wollongong, Australia

Safe and effective locomotion depends critically on judgements of the surface properties of the ground to be traversed. Little is known about the role of binocular vision in surface perception at distances relevant to visually guided locomotion in humans. Programmable arrays of illuminated targets were used to present sparsely textured surfaces with real depth at distances of 4.5 and 9.0 m. Psychophysical measurements of discrimination thresholds demonstrated a clear superiority for stereoscopic over monocular judgments of relative and absolute surface slant. Judgements of surface roughness in particular demonstrated a substantial binocular advantage. Binocular vision is thus shown to directly contribute to judgements of the layout of terrain up to at least 4.5 m, and its smoothness to at least 9.0 m. Hence binocular vision could support moment-to-moment wayfinding and path planning, especially when monocular cues are weak.

Keywords: stereopsis, slant, binocular vision, smoothness, depth perception, discrimination

Citation: Allison, R. S., Gillam, B. J., & Palmisano, S. A. (2009). Stereoscopic discrimination of the layout of ground surfaces. *Journal of Vision, 9*(12):8, 1–11, http://journalofvision.org/9/12/8/, doi:10.1167/9.12.8.

Introduction

Active movement through the environment requires critical judgements of the slope, layout and regularity of the ground. Safe movement often depends on the accuracy of these judgements made several meters away—say 2–25 m for walking, running or cycling (Cutting, Springer, Braren, & Johnson, 1992; Land, 2006; Marigold & Patla, 2007; Wilkie & Wann, 2003; Wilkie, Wann, & Allison, 2008). Although binocular disparity is known to be one of the primary cues to depth and slant at near distances, there has been little research on binocular influences on perceived surface layout at distances beyond 1–2 m. Studies of binocular vision at greater distances have focused on judgments of absolute distance and depth thresholds rather than the suprathreshold perception of depth and slant. Perhaps because binocular disparity, the cue for stereoscopic depth perception, declines rapidly with distance it is generally believed that binocular depth cues are ineffective beyond very modest distances (Gregory, 1966; McKee, Levi, & Bowne, 1990). However, given the precision of stereo acuity (Howard, 1919), geometrical analysis suggests that it should be possible to obtain useful information from stereopsis at much larger distances than conventionally assumed and we have demonstrated binocular improvements in depth interval discrimination and estimation to a distance of 18 m (Allison, Gillam, & Vecceli o, 2009). In the present study we investigate the contribution of stereopsis to the perception of ground surface slant and smoothness at a distance beyond interaction space using real surfaces. In three experiments, we provide evidence that binocular viewing considerably improves the discrimination of terrain layout 4.5 m away and smoothness of surfaces 9.0 m away (an important range for moment-to-moment path planning during walking, running and assisted travel).

One of the few directly relevant previous studies is by Wu, He, and Ooi (2007) who infer, from their measurements of absolute distance, an upward slant bias of the perceived ground plane at distances greater than 2–3 m. They tested this inference (using virtual reality) by having observers adjust a far surface to the perceived level of the nearer ground plane (which had a different texture) at distances of 3–5 m. They found an upward slope but their measurement (entirely stereoscopic) did not allow any evaluation of whether there is a stereoscopic advantage.

Another relevant study by Feresin and Agostini (2007) found that slant matches to full-cue photographs of inclined, natural ground planes located 4–6 m away were significantly biased uphill when viewed monocularly but were accurate when presented stereoscopically.

Previous studies of stereoscopic slant perception (of which there have been many) have been conducted at close distances (less than 2 m) and usually relative to the frontal plane. In the present experiments we use real displays, which avoids the residual cue conflict present in computer displays. Knill and Saunders (2003) used an inclined monitor (40 degrees) and shutter glasses to minimize cue conflict at larger slants and obtained slant

doi: 10.1167/9.12.8 Received July 14, 2009; published November 17, 2009 ISSN 1534-7362 © ARVO

discrimination thresholds between sequentially presented isolated planar stimuli. However, these data were obtained at a close distance (60 cm) and do not investigate how well observers can make judgements of either the absolute slant of a ground surface relative to the horizontal, the change in slant across the ground, or of the smoothness of a surface, which were the three tasks we used.

Identifying an independent stereoscopic contribution to ground plane perception is difficult due to logistical issues related to presenting real controlled stimuli at a distance. While some of these issues can be resolved using virtual environments, concerns have been raised about the results of such studies, as distance judgments tend to be far less veridical than those obtained in real 3-D environments (Bingham, Bradley, Bailey, & Vinner, 2001; Ellis & Menges, 1997; Knapp & Loomis, 2004; Tcheang, Gilson, & Glennerster, 2005; Wann, Rushton, & Mon-Williams, 1995; Willemsen, Colton, Creem-Regehr, & Thompson, 2009). We address the logistical issues arising from the use of real depth stimuli with a novel three-dimensional, distributed arrangement of programmable, wirelessly controlled lights that could be selectively and rapidly configured to present a variety of slants at a given distance. In separate two-alternative forced choice experiments observers discriminated: 1) the absolute slant of a single plane; 2) the relative slant between two adjacent planes; or 3) whether all the lights lay in a single plane or not (surface smoothness). This allowed us to assess the ability to judge absolute slant of a ground plane, the sensitivity to relative slant on a ground plane, and the ability to discern the smoothness of extended surfaces provided by binocular vision.

Methods

General methods and apparatus

Observers sat at a bench with their head supported by a chinrest. A platform was mounted beneath the bench at a height of 25 cm from the actual floor. This platform provided a false floor elevated to the same height above the real floor as the stimulus. The observer viewed the display from a nominal eye height of 116 cm from the platform. This configuration allowed presentation of stimuli with slants relative to a horizontal ground plane at a normal seated eye height.

A rectangular aperture subtending 28° wide by 20° high was located at a distance of 48 cm from the observer to define the field of view. The room lights were extinguished and extraneous light sources eliminated so that the room, floor and apparatus were not visible with the stimulus displayed. Participants were light adapted prior to each experimental session or block and confirmed that nothing was visible besides the lights.

The stimuli consisted of an array of light emitting diodes (LEDs; RL5-R5015, 634 nm peak wavelength, 5 mm diameter, Super Bright LEDS Inc, St. Louis, Missouri, USA) that that could be rapidly reconfigured in different combinations. The lights were interfaced to a set of microcontroller-based intelligent driver boards. These driver boards were networked together into a single scalable display network. The arrangement allows for configurations of hundreds of lights, with approximately one hundred lights used in these experiments (only a subset was illuminated at any one time). These processor boards could set the brightness of individual lights to one of 254 levels (via pulse-width modulation at 32,000 Hz which allowed precise control with no visible flicker), set the light to flash at regular intervals, or turn the light on or off. The microcontrollers were interfaced to a Macintosh Powerbook G4 laptop via a Bluetooth wireless link. This machine served as the main experimental control computer running custom software to select and illuminate sets of lights. This method allows instant changes in targets as any subset of LEDs (and their intensity and timing) could be illuminated under computer control. For example any slant or set of slants could be presented with the press of a button (or step in an experimental script) switching on a precomputed subset of the LEDs.

The computer-controlled constellation of LEDs was distributed throughout a volume of space centered 4.5 or 9.0 m from the observer. A forest of 16 vertical metal posts was irregularly positioned on the floor of the lab within a space extending 1.0 m laterally and 2.6 m in depth. Six lights were precisely positioned on each post at different heights. Lights could be illuminated in any combination. The lights were distributed in depth and thus provided binocular cues to relative depth between them and formed a flexible, distributed three-dimensional display. Monocular cues were also present but relatively weak due to the small size of the LEDs and the irregular and unpredictable pattern of the lights.

For these experiments, the lights were precisely arranged in front of the observer into planes that extended laterally and in depth at a given geographical slant. The lights were arranged in six planes with geographical slant about a horizontal axis of −5, −3, −1, 1, 3, and 5°. These planes could be illuminated fully or partially, singly or in combination with any other set of lights in the display. In these experiments, LEDs were selectively lit to create a single ground plane, two adjacent planes or two interleaved planes (simulating uneven terrain).

The order of presentation was controlled by custom software. Observers made verbal responses that were keyed into the computer by the experimenter. Stimuli were displayed until the subject responded, which was typically 1–2 s. No feedback was provided to the observer. Viewing was binocular or monocular (with the observers' non-dominant eye patched with an opaque eye patch).

Experiment 1: Geographical slant discrimination

Seven observers with normal stereopsis (based on screening with the Randot stereo test) participated. Five were naïve with regard to the experimental conditions and two were experimenters. All had normal or corrected-to-normal vision. On each trial, nine lights were illuminated corresponding to a single plane (single surface) slanted with respect to the horizontal at −5, −3, −1, 1, 3, or 5° (Figure 1). The nine lights were chosen randomly from 16 possible lights to ensure variety and unpredictability in the pattern of lights presented. Each slant was repeated 20 times over the course of four sessions, two each for both monocular and binocular viewing in counterbalanced order. Viewing distance was 450 cm to the center of the display. Observers were required to indicate whether the surface appeared to be sloping uphill or downhill with respect to a flat, level ground plane (i.e., with respect to their internal representation of earth level) in a two-alternative, forced-choice procedure. The method of constant stimuli was employed, psychometric curves were fitted and thresholds estimated using probit analysis (Finney, 1971).

Experiment 2: Relative slant discrimination

Six observers with normal stereopsis participated. Four were naïve and two were experimenters; four also participated in Experiment 1. All had normal or corrected-to-normal vision except one who had reduced visual acuity (20/25) in one eye due to cataract. This observer's data were similar to the others.

We presented two abutting surfaces (Figure 2), one behind (more distant than) the other, with a range of relative slants between them and a variety of mean slants across the pair. On each trial, five posts in the rear half of the display were selected randomly and lights set at one slant and five light positions in the front half were selected and set to a different slant. Objectively the two virtual planes intersected at the middle where they abutted. Four additional lights in the center of the display were illuminated at the common intersection of the surfaces. Thus, nine co-planar lights defined each surface.

Observers were required to judge whether the angle formed by these two slanted surfaces was convex (peaked like a roof) or concave (like a valley), viewing the stimuli binocularly or monocularly in separate sessions. Slant pairs (5°, −1°; −5°, 1°; −3°, 3°; −1°, 5°; 1°, −5°; 3°,

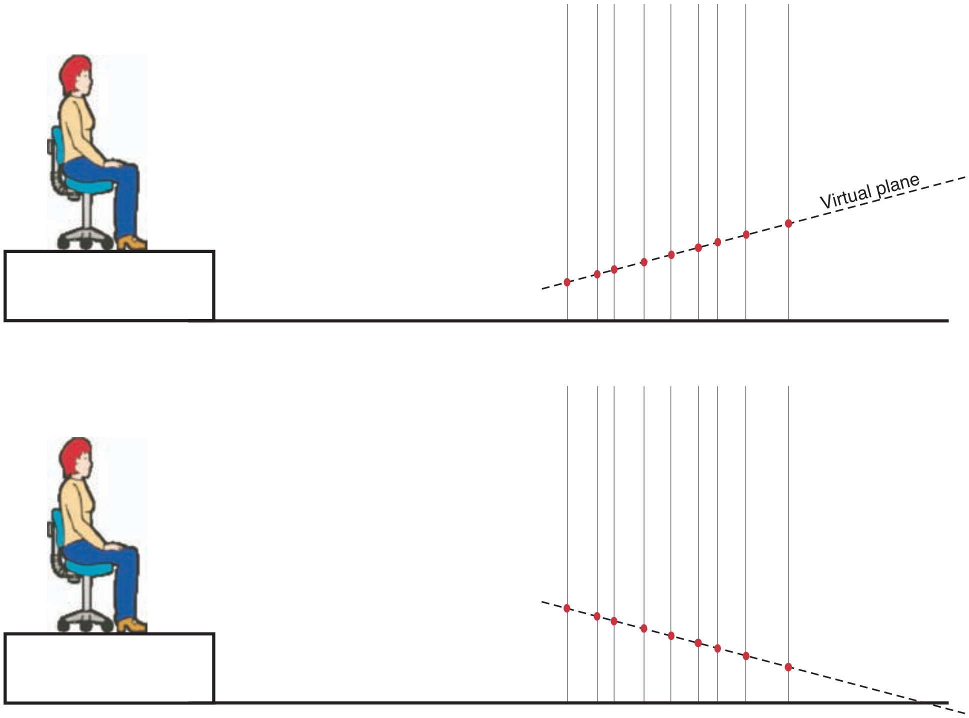

Figure 1. Geographical slant discrimination under monocular and binocular viewing at a distance of 4.5 m from the observer to the center of the configuration (Experiment 1). Schematic side view of the viewing situation for uphill (top) or downhill (bottom) virtual planes (these surface patches are depicted edge-on in the diagram). Note the greater texture compression for downhill. For ease of illustration, the chinrest, viewing aperture and other details are not shown. Subjects perceived a sparse set of lights lying in a plane, shown edge-on in the illustration. The lights were mounted on irregularly spaced poles distributed throughout a volume of space and a random subset of lights was illuminated providing an unpredictable pattern of projection on the retina.

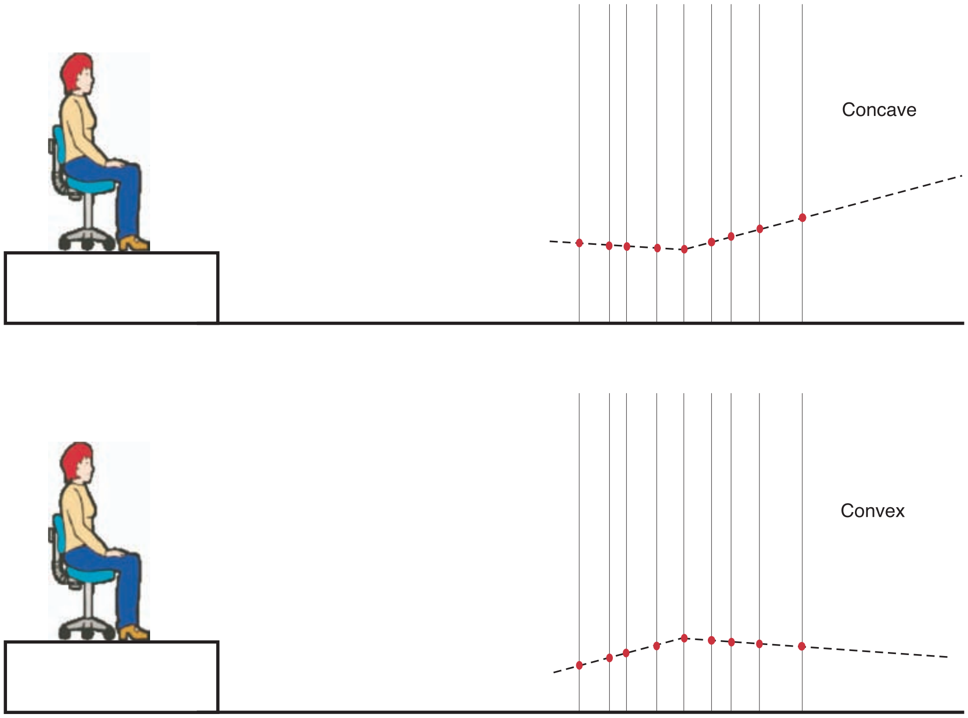

Figure 2. Discrimination of relative slant in adjacent surfaces under monocular and binocular viewing at 4.5 m (Experiment 2). Schematic side view of the viewing situation for concave (top) and convex (bottom) arrangements of virtual planes, seen edge on in the illustration but as extended 3D surfaces by the observer.

−3°; 1°, −3°; −3°, 1°; −1°, 3°; 3°, −1°; 5°, 1°; 1°, 5°; −3°, −1°; −1°, −3°; 3°, 1°; 1°, 3°; 1°, −1°; −1°, 1°) were chosen to give slant differences of ±6°, ±4°, and ±2° with average slants of 0°, ±1°, or ±2°. Each pair was repeated twenty times according to the method of constant stimuli for each monocular and binocular viewing condition over the course of four sessions, two each for both monocular and binocular viewing in counterbalanced order. Viewing distance was 450 cm.

Experiment 3: Surface smoothness discrimination

In the final experiment, we considered judgements of surface smoothness/flatness. This is possibly the most significant potential advantage of binocular vision over monocular vision. Detection of uneven terrain is essential for safe and efficient locomotion. To our knowledge however the contribution of binocular vision to the perception of ground surface smoothness has not been investigated before at any distance. This judgment will depend on local variations in relative disparity. We devised a task that relied on processing local variations in relative disparity and produced perceptions of ground surface roughness or smoothness. We presented two superimposed, planar random LED surfaces at slightly different slants relative to a simulated ground plane. These surfaces intersected and passed through each other in the center of the LED configuration. We asked whether subjects could discriminate a single surface from a pair of intersecting surfaces for a variety of slant differences and mean slants (Figure 3). It should be noted that unlike Experiment 2, where participants judged the relative slant of abutting surfaces, in this experiment there were rich local variations in relative disparity information. In the binocular conditions of Experiment 3 there was no sense of there being two separate surfaces with the small slant differences that we were testing. As the slant difference increased the stimulus took on the impression of a rough surface rather than a smooth surface. Observers were informed that on half the trials the lights would represent a single planar surface (a slant difference of zero) and that on the remaining trials the lights would not lie on a single planar surface. The observers were required to detect the single surface conditions in a yes–no experiment. Sensitivity (d') and its variance were estimated for each condition using signal detection theory (Green & Swets, 1966; Macmillan & Creelman, 1991). Specifically, $d' = z(H) - z(F)$, where z(x) is the z-score for rate x (from the inverse cumulative normal distribution). H is the hit rate and is estimated by the proportion of 'single planar surface' responses on trials when a single stimulus was in fact presented (i.e. across all of the 0° slant difference trials). H was estimated separately for each viewing distance by viewing condition (monocular vs. binocular)

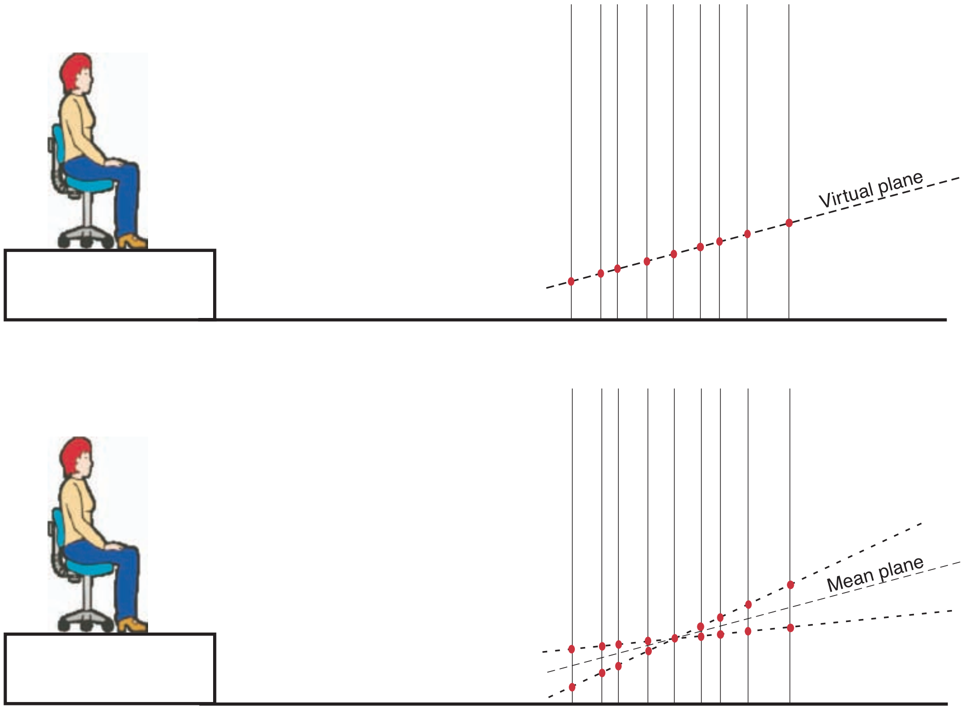

Figure 3. Task for the observer in the surface smoothness/flatness judgements experiment (Experiment 3). Schematic side view of the viewing situation for single (top) or double intersecting (bottom) virtual planes, seen edge on in the illustration but as extended 3D surfaces by the observer.

combination. Likewise, F is the false-alarm rate and is estimated by the proportion of 'single planar surface' responses on trials when a single planar surface was *not* presented. For each observer, F and subsequently *d*′ were calculated for each slant difference at each viewing distance by viewing condition combination.

Six observers with normal stereopsis participated. Four were naïve and two were experimenters; four also participated in Experiments 1 and 2. All had normal or corrected-to-normal vision except one who had reduced visual acuity (20/25) in one eye due to cataract. Additional scrutiny was paid to this observer's data that again indicated performance at a similar level to the others.

On each trial, five posts out of the sixteen were selected randomly and lights set at one slant and another five lights were selected and set to either the same or a different slant. Four additional lights in the center of the display were at the common intersection of the surface. Thus, nine co-planar lights defined each surface. Slant pairs (5°, −1°; −5°, 1°; 5°, 1°; −3°, 3°; 1°, −3°; −1°, 3°; −3°, −1°; 3°, 1°; −1°, 1° plus −5°, −5°; −3°, −3°; −1°, −1°; 1°, 1°; 3°, 3°; 5°, 5°) were chosen to give either slant differences of 6°, 4°, and 2° or no slant difference (which was the target condition).

The experiment was run at viewing distances of 450 cm and 900 cm. At each distance, the data were collected over the course of four sessions, two each for both monocular and binocular viewing in counterbalanced order. Across these two sessions, each slant difference condition was presented 24 times (collapsed across mean slants for each slant difference with 8 repeats per slant-pair) resulting in 72 objectively 'double' trials that were balanced by 72 objectively 'single' conditions per combination of viewing condition and distance.

Results

Experiment 1: Geographical slant discrimination

First we considered whether stereopsis helps in the estimation of absolute slant at a distance. Specifically, we asked whether binocular vision improves the ability to discriminate the slope of a surface from horizontal (i.e., its geographical slant).

Psychometric functions for the observer's slant discrimination were obtained and plotted as the proportion of uphill responses as function of true slant (Figure 4 top). Monocularly, at 4.5 m, subjects had a strong bias toward seeing the plane as uphill confirming earlier reports (Feresin & Agostini, 2007; Gibson, Olum, & Rosenblatt, 1955). Several subjects reported that the plane always looked uphill (or even frontal) and that they had to infer the

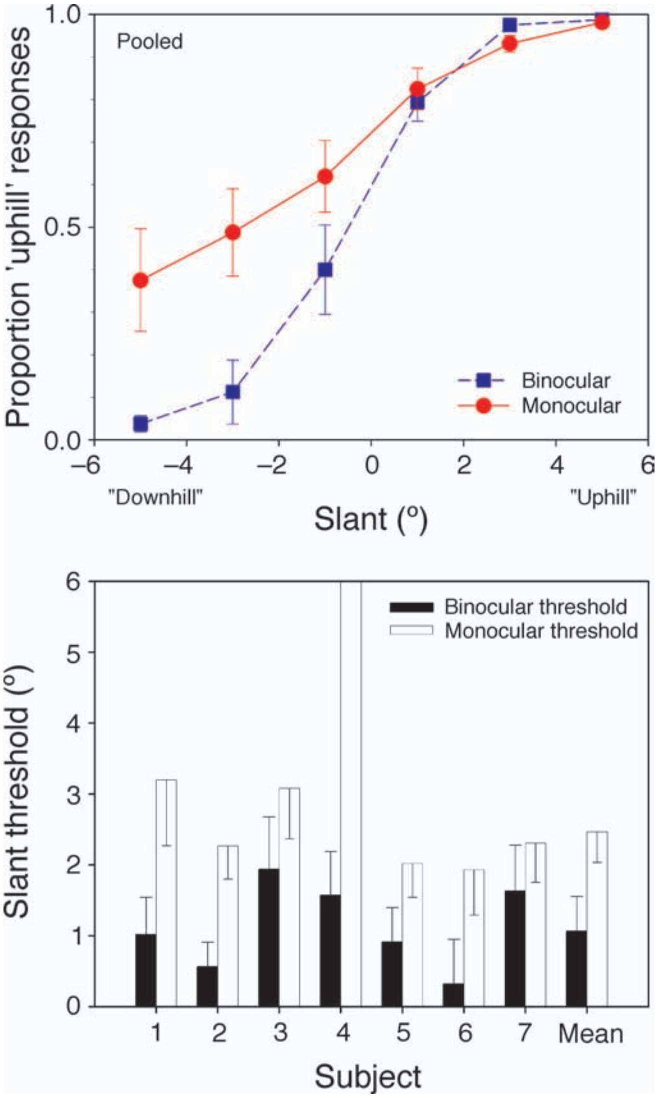

Figure 4. Slant discrimination (Experiment 1) under monocular and binocular viewing at a distance of 4.5 m from the observer to the center of the configuration. The lights were mounted on irregularly spaced poles distributed throughout a volume of space and a random subset of lights was illuminated to represent a given slant via an unpredictable pattern of projection on the retina. Top: The pooled psychometric function (across the six observers) of the proportion of trials reported as 'uphill' as a function of the geographic slant of the surface. Positive slant angles correspond to objectively uphill slant. Bottom: Discrimination thresholds (equivalent to unbiased discrimination performance of 75% correct) from probit analysis for each observer. Error bars indicate 95% confidence intervals.

slant. Despite this, subjects could perform the task and gave monotonically increasing proportions of uphill responses as the surface slant increased (positive slant corresponds to uphill slant). Binocularly, however, subjects were able to discriminate the slant much more precisely and with less bias (the uphill monocular bias is reflected in the significant shift in the point of subjective equality away from true horizontal in Figure 4, top). Subjectively, subjects reported accurately that the configuration of lights appeared to lie near the ground plane when viewed binocularly. The slope of the psychometric function was much steeper for binocular than monocular viewing, indicating a greater sensitivity to changes in slant for binocular viewing (significantly different, paired *t*-test: $t(5) = 6.46$, two-tailed $p = 0.0013$). Figure 4, bottom shows measured binocular and monocular thresholds estimated from these slopes.

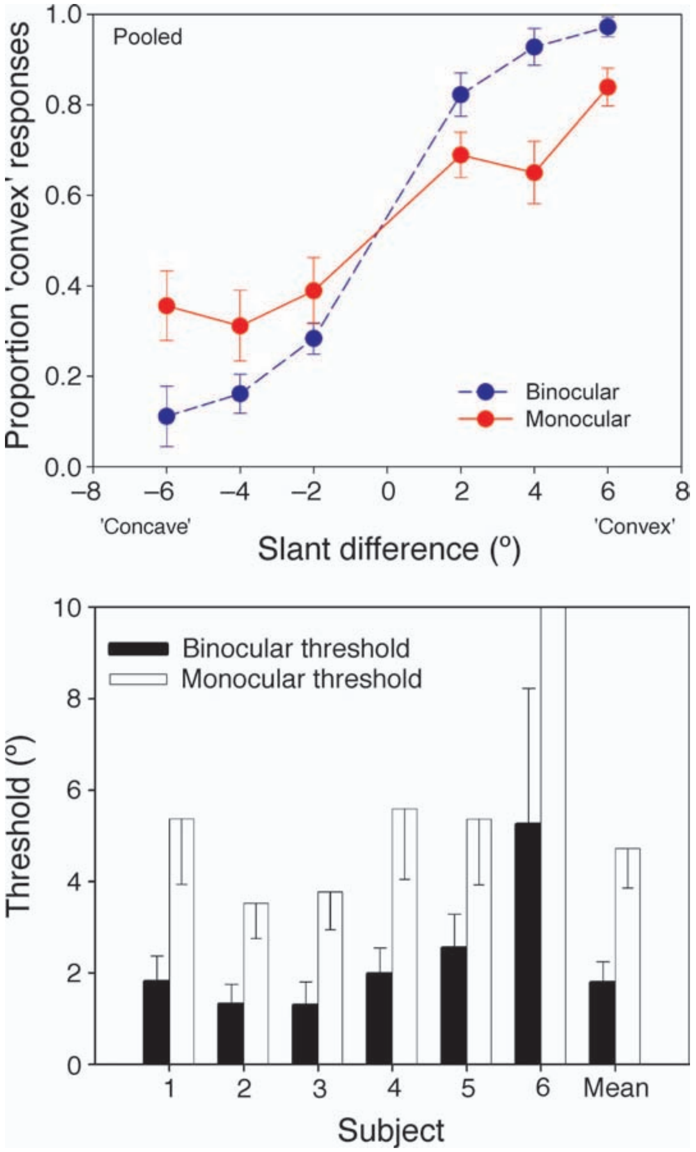

Figure 5. Discrimination of relative slant in adjacent surfaces under monocular and binocular viewing at 4.5 m (Experiment 2). Top: Psychometric functions were obtained for the six observers. The proportion of convex responses is plotted as function of slant difference which is coded as positive for an objectively convex difference and negative for an objectively concave difference. Bottom: Discrimination thresholds (75%) from probit analysis for each observer. Error bars indicate 95% confidence intervals.

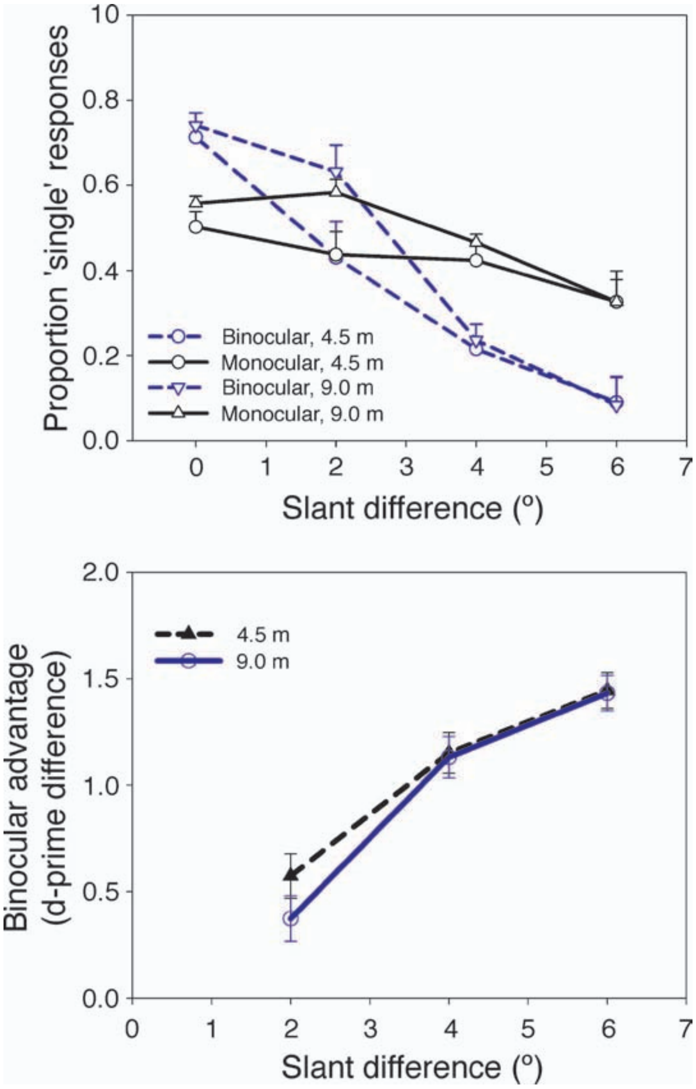

Figure 6. Surface smoothness discrimination (Experiment 3). Top: The curves show the proportion of trials for which the observers reported "single surface" for monocular and binocular viewing as a function of slant difference between the virtual planes (pooled across observers, N = 6; error bars indicate standard error). When the slant difference was zero, a single plane was actually presented. Bottom: Sensitivity for discriminating two planes trials from single plane (zero slant difference) trials. The plot shows the *increase* in sensitivity provided by binocular viewing. The binocular advantage—the difference between binocular and monocular sensitivities—is expressed in terms of difference in signal detection theory sensitivity (d'). Positive values indicate a greater sensitivity for binocular conditions for a given slant difference. Error bars indicate 95% confidence intervals.

Experiment 2: Relative slant discrimination

In a second experiment we asked whether stereopsis helps discriminate the difference in slant between two surfaces at a distance. Observers were required to judge whether the angle formed by these two slanted surfaces was convex (peaked like a roof) or concave (like a valley).

Psychometric functions were obtained for both monocular and binocular viewing (Figure 5). As the stimulus went from concave to more and more convex the proportion of convex responses increased as expected but the curves were steeper binocularly indicating greater binocular sensitivity. Estimated thresholds from these functions indicated that binocular thresholds were lower by a factor of at least 2–3 than monocular thresholds (significantly different, paired t-test: $t(5) = 10.40$, two-tailed $p = 0.0005$).

Experiment 3: Surface smoothness discrimination

In the final experiment, we considered judgements of surface smoothness/flatness. Here smoothness perception was evaluated by asking whether subjects could discriminate a single surface from a pair of intersecting surfaces (Figure 3).

Figure 6, top shows the proportion of single surface responses as a function of slant difference for both monocular and binocular viewing. At zero degree separation the stimulus was in fact single and not surprisingly this was the stimulus most likely to be judged single. With binocular viewing, subjects were more likely to report the objectively single surface as single than with monocular viewing. Conversely when there was a slant difference, subjects were less likely to mistakenly report it as single with binocular viewing.

Binocular viewing produced more hits and fewer false alarms than monocular viewing, and hence demonstrated greater sensitivity (Table 1). Monocularly, subjects performed very poorly at the task for all slant differences. We can compare monocular and binocular sensitivities by considering the binocular advantage obtained by subtracting monocular from binocular sensitivity. Sensitivity was computed by calculating d'. In Figure 6 bottom, we plot the difference in binocular and monocular sensitivity or d' as a function of slant difference. The plot demonstrates that in all cases binocular viewing significantly improves

		Sensitivity (d')	
Distance	Slant Difference	Monocular	Binocular
4.5 m	2°	0.16	0.74
	4°	0.20	1.35
	6°	0.46	1.90
9.0 m	2°	−0.06	0.31
	4°	0.23	1.36
	6°	0.60	2.03

Table 1. Mean sensitivity in Experiment 3.

sensitivity at both 4.5 and 9.0 m, particularly at large slant differences.

Discussion

The binocular advantages we observed in the tasks outlined above were almost certainly due to the stereopsis provided by binocular vision. Binocular vision confers other benefits to an observer (e.g., binocular summation and vergence-mediated distance perception), but stereopsis is the only binocular cue known to provide the level of precision we obtained. Depth estimation based upon vergence changes is much less precise and in any case is ineffective beyond about 2.0 m (Tresilian, Mon-Williams, & Kelly, 1999). The increased sensitivity we found with binocular viewing was also much larger than could be expected based on binocular/probability summation (Baker, Meese, & Georgeson, 2007).

The precision of stereopsis allows it to be effective for depth judgements at moderate to large distances (for a recent review see Allison et al., 2009). However, stereoacuity for depth discrimination between two points is not a good predictor of stereoscopic slant sensitivity (Allison, Rogers, & Bradshaw, 2003; Bulthoff, Fahle, & Wegmann, 1991; Fahle & Westheimer, 1988; Gillam, Blackburn, & Brooks, 2007; Gillam & Pianta, 2005; Gogel & Mershon, 1977; Mitchison & McKee, 1990; Pierce, Howard, & Feresin, 1998; Poom, Olsson, & Borjesson, 2007; van Ee, Banks, & Backus, 1999; Werner, 1937; Westheimer, 1979), which must be measured in it own right.

It is well known that shear disparity or disparity gradient (i.e. minutes of disparity per minute of visual angle) along a surface with a given oculocentric slant about a horizontal axis varies approximately inversely with its distance (Ogle, 1964), while the local relative disparities scale approximately with the inverse of the distance squared. Thus, disparity gradient is less affected by distance than disparity per se. The situation is complicated by the fact that a flat ground plane surface does not have constant oculocentric slant but rather its slant increases with distance. As discussed in Allison et al. (2009), this means that along the ground plane in depth, the disparity change per change in visual angle is approximately constant.

Binocular slant information could theoretically result from responding to gradients of binocular disparity. However there is evidence that stereo slant perception is based on higher order patterns of disparity such as differences in shear or compression between the left and right eye images (Gillam, Chambers, & Russo, 1988). Since our experiments involved slant around a horizontal axis, gradients of shear are likely to have been the primary stimulus. In experiment 3 local relative disparities were likely to be critical in the detection of roughness.

This study refutes the commonly held notion that only near tasks can benefit from stereopsis. Most stereoscopic research at distances beyond 2 m has concentrated on the binocular perception of absolute distances (Crannell & Peters, 1970; Morrison & Whiteside, 1984), depth constancy (Allison et al., 2009; Durgin, Proffitt, Olson, & Reinke, 1995; Loomis & Philbeck, 1999), and depth discrimination (e.g., Howard, 1919). The present study is the first to our knowledge to consider the stereoscopic perception of real ground surface properties not only at greater distances, but at any distance. Judgements of depth-to-width aspect ratio of objects lying on the ground plane (e.g., Loomis & Philbeck, 1999) are of course affected by the slant of the ground (Ooi, Wu, & He, 2006) but aspect ratio judgements do not require ground slant judgements (Durgin et al., 1995). We find that stereoscopic judgements are consistently and significantly superior to monocular judgments of absolute surface orientation, relative surface orientation, and surface roughness. It is particularly interesting that the uphill bias we found monocularly, and that Wu et al. (2007; Wu, Ooi, & He, 2004) infer from distance measures in a number of studies at distances of >2–3 m, disappeared in our slant discrimination task with binocular viewing (Experiment 1). The superiority we found for binocular vision at these larger distances cannot be due to integrative processes over the ground plane from near to far, as proposed by SSIP theory (Wu et al., 2004) as there was nothing visible in near space. While such processes may play a role in the interpretation of monocular cues at a distance, it is clear from the present results that stereopsis can directly support slant perception at a distance.

In everyday visually guided action stereopsis will operate in concert with other cues to surface layout to provide judgements of the traversability and support provided by the terrain. Indeed other work has demonstrated that slant perception may be optimized or biased for perception on the ground plane as suggested by Gibson (1950). For example, Bian, Braunstein, and Andersen (2005) found a strong preference for interpreting optical contact information in terms of the ground plane compared to contact with ceiling or wall planes. Such a bias appears to result from interpretation of the surface as a ground plane rather than from the surface's location in the visual field (Bian, Braunstein, & Andersen, 2006). Similar biases may exist in stereopsis. For instance, it has been consistently demonstrated that psychophysically determined corresponding vertical meridia in the two eyes are relatively extorted. This well-known shear of empirically corresponding binocular points has been interpreted as an evolutionary adaptation of binocular vision to favor ground plane perception (Helmholtz, 1909; Siderov, Harwerth, & Bedell, 1999). Such an extortion results in an inclination of the vertical horopter that increases with distance favoring precise depth perception on the ground plane. In the present study we made no comparisons of ground plane judgements with similar judgements on other planes. As a result we make no claim that such judgements are more precise on the ground plane. However, as such a claim is consistent with current theories of stereopsis, we intend to test this hypothesis in future work.

Although binocular viewing significantly improved performance observers could perform the tasks to some extent monocularly. Texture cues in our sparse irregular light patterns, while present and appropriate for the slant, did not support precise and accurate slant judgements. Importantly, these weak monocular cues allowed the binocular contribution to be better evaluated. The main cue available monocularly was texture compression along the direction perpendicular to the axis of slant produced by the highly oblique angle formed between the ground plane and the line of sight. This was particularly strong when the surface slanted downhill. Several subjects reported that they used this compression cue even when the monocular surface did not appear to be a convincing ground plane. Compression becomes more pronounced as distance increases since the angle of the horizontal to the line of sight increases (Knill & Saunders, 2003). Compression of the texture was thus a potential cue for monocular discrimination in Experiments 1 and 2. However, the overlap of the two surfaces in Experiment 3 would have made it difficult to detect and utilize this texture compression cue. This may explain why the binocular advantage was more pronounced in the final experiment.

It is possible that binocular vision would not have displayed superiority over monocular vision for the slant tasks we used if full linear perspective cues were available (although it is likely that it would continue to do so for the smoothness task). However, our demonstration that binocular vision provides effective cues to important surface properties at distances where it is usually considered perceptually non-functional has theoretical importance. From a practical point of view there are a number of environmental situations in which the available monocular information is inadequate for locomotion. For example, when one walks or runs on trails, footpaths and fields without linear perspective, particularly at night. It is an empirical matter to determine the role that binocular vision plays when monocularly available information is increased (to varying degrees). We intend to pursue this issue in our future research.

The most striking binocular advantage was for discerning the smoothness of extended surfaces at both 4.5 and 9.0 m. The aim in Experiment 3 was to simulate very local surface roughness/irregularity of the kind that occurs in the natural world for a stony path or a leaf covered ground. Texture gradients are not local enough to be important under these conditions but shading, occlusion and motion parallax may play a role. These cues were non-existent in our stimuli due to the sparse texture, irregular light spacing and immobilized head. Stereopsis may be particularly useful in judgements of ground surface regularity when these monocular cues are lacking. Beyond limited cue conditions, stereopsis may be important due to the superior information it provides, compared to other cues, with respect to quantitative local depth variations.

It is becoming apparent that binocular eye movements and vision are important for locomotor behavior in walkers with normal binocular vision, especially for avoiding obstacles. Patla, Niechwiej, Racco, and Goodale (2002) found that accuracy of limb elevation when stepping over an obstacle was degraded under monocular compared to binocular viewing. Specifically, participants exaggerated limb motions when walking with monocular compared to binocular vision. Binocular vision seemed to affect the planning of the step, rather than its execution, since restoring binocular vision during the step did not improve step accuracy. Hayhoe, Gillam, Chajka, and Veccelio (2009) reported that subjects were 10% slower and exaggerated limb movements when avoiding obstacles under monocular compared with binocular viewing. They also recorded eye fixations and found that, during monocular viewing, subjects tended to fixate obstacles longer and also to fixate near the stepping location six times as often compared to during binocular viewing. They interpreted these findings as adaptive behavior to compensate for degraded spatial perception in the absence of stereopsis.

In summary, the three experiments presented here investigated the binocular perception of real ground surfaces at distances relevant to safe and effective locomotion. We found a considerable superiority for binocular judgements over monocular judgments for absolute surface orientation, relative surface orientation, and surface smoothness in sparse patterns. Binocular discrimination of absolute and relative slant showed less bias and was more precise than monocular discrimination. The binocular advantage was most pronounced for the surface smoothness discrimination task. Judgements of surface smoothness were very difficult monocularly compared to binocularly, as reflected in substantial differences in sensitivity. We conclude that, binocular vision can contribute to judgements of the layout at 4.5 m and to judgements of smoothness of terrain to at least 9.0 m—ranges of considerable importance for locomotion and moment-to-moment wayfinding or path planning.

Acknowledgments

This research was supported by an Australian Research Council Linkage International Fellowship to BG and RA, an ARC Discovery Grant to BG and a NSERC Discovery Grant to RA. Thanks to John Fowler and Joao Araujo for assistance with the apparatus and to

Elia Vecellio for assistance with the design and conduct of the experiments.

Commercial relationships: none.

Corresponding author: Robert Allison.
Email: allison@cse.yorku.ca.
Address: Centre for Vision Research, York University, 4700 Keele Street, Toronto ON, Canada M3J 1P3.

References

Allison, R. S., Gillam, B. J., & Veccelio, E. (2009). Binocular depth discrimination and estimation beyond interaction space. *Journal of Vision, 9*(1):10, 1–14, http://journalofvision.org/9/1/10/, doi:10.1167/9.1.10. [PubMed] [Article]

Allison, R. S., Rogers, B. J., & Bradshaw, M. F. (2003). Geometric and induced effects in binocular stereopsis and motion parallax. *Vision Research, 43,* 1879–1893. [PubMed]

Baker, D. H., Meese, T. S., & Georgeson, M. A. (2007). Binocular interaction: Contrast matching and contrast discrimination are predicted by the same model. *Spatial Vision, 20,* 397–413. [PubMed]

Bian, Z., Braunstein, M. L., & Andersen, G. J. (2005). The ground dominance effect in the perception of 3-d layout. *Perception & Psychophysics, 67,* 802–815. [PubMed] [Article]

Bian, Z., Braunstein, M. L., & Andersen, G. J. (2006). The ground dominance effect in the perception of relative distance in 3-d scenes is mainly due to characteristics of the ground surface. *Perception & Psychophysics, 68,* 1297–1309. [PubMed] [Article]

Bingham, G. P., Bradley, A., Bailey, M., & Vinner, R. (2001). Accommodation, occlusion, and disparity matching are used to guide reaching: A comparison of actual versus virtual environments. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 1314–1334. [PubMed]

Bulthoff, H., Fahle, M., & Wegmann, M. (1991). Perceived depth scales with disparity gradient. *Perception, 20,* 145–153. [PubMed]

Crannell, C. W., & Peters, G. (1970). Monocular and binocular estimations of distance when knowledge of the relevant space is absent. *The Journal of Psychology, 76,* 157–167. [PubMed]

Cutting, J. E., Springer, K., Braren, P. A., & Johnson, S. H. (1992). Wayfinding on foot from information in retinal, not optical, flow. *Journal of Experimental Psychology: General, 121,* 41–72. [PubMed]

Durgin, F. H., Proffitt, D. R., Olson, T. J., & Reinke, K. S. (1995). Comparing depth from motion with depth from binocular disparity. *Journal of Experimental Psychology-Human Perception and Performance, 21,* 679–699. [PubMed]

Ellis, S. R., & Menges, B. M. (1997). Judgments of the distance to nearby virtual objects: Interaction of viewing conditions and accommodative demand. *Presence-Teleoperators and Virtual Environments, 6,* 452–460. [PubMed]

Fahle, M., & Westheimer, G. (1988). Local and global factors in disparity detection of rows of points. *Vision Research, 28,* 171–178. [PubMed]

Feresin, C., & Agostini, T. (2007). Perception of visual inclination in a real and simulated urban environment. *Perception, 36,* 258–267. [PubMed]

Finney, D. J. (1971). *Probit analysis*. London: Cambridge University Press.

Gibson, J. J. (1950). *The perception of the visual world*. Boston: Houghton Mifflin.

Gibson, J. J., Olum, P., & Rosenblatt, F. (1955). Parallax and perspective during aircraft landings. *American Journal of Psychology, 68,* 372–385. [PubMed]

Gillam, B. J., Blackburn, S., & Brooks, K. (2007). Hinge versus twist: The effects of 'reference surfaces' and discontinuities on stereoscopic slant perception. *Perception, 36,* 596–616. [PubMed]

Gillam, B. J., Chambers, D., & Russo, T. (1988). Postfusional latency in slant perception and the primitives of stereopsis. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 163–175. [PubMed]

Gillam, B. J., & Pianta, M. J. (2005). The effect of surface placement and surface overlap on stereo slant contrast and enhancement. *Vision Research, 45,* 3083–3095. [PubMed]

Gogel, W. C., & Mershon, D. H. (1977). Local autonomy in visual space. *Scandinavian Journal of Psychology, 18,* 237–250. [PubMed]

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.

Gregory, R. L. (1966). *Eye and brain*. London: World University Library.

Hayhoe, M., Gillam, B., Chajka, K., & Veccelio, E. (2009). The function of binocular vision in walking. *Visual Neuroscience, 26,* 73–80. [PubMed]

Helmholtz, H. v. (1909). *Physiological optics. English translation 1962 by J. P. C. Southall from the 3rd German edition of handbuch der physiologischen optik. Vos, Hamburg*. New York: Dover.

Howard, H. J. (1919). A test for the judgment of distance. *Transactions of the American Ophthalmological Society, 17,* 195–235. [PubMed] [Article]

Knapp, J. M., & Loomis, J. M. (2004). Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence-Teleoperators and Virtual Environments, 13,* 572–577.

Knill, D. C., & Saunders, J. A. (2003). Do humans optimally integrate stereo and texture information for judgments of surface slant? *Vision Research, 43,* 2539–2558. [PubMed]

Land, M. F. (2006). Eye movements and the control of actions in everyday life. *Progress in Retinal and Eye Research, 25,* 296–324. [PubMed]

Loomis, J. M., & Philbeck, J. W. (1999). Is the anisotropy of perceived 3-d shape invariant across scale? *Perception & Psychophysics, 61,* 397–402. [PubMed]

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A users guide*. New York: Cambridge University Press.

Marigold, D. S., & Patla, A. E. (2007). Gaze fixation patterns for negotiating complex ground terrain. *Neuroscience, 144,* 302–313. [PubMed]

McKee, S. P., Levi, D. M., & Bowne, S. F. (1990). The imprecision of stereopsis. *Vision Research, 30,* 1763–1779. [PubMed]

Mitchison, G. J., & McKee, S. P. (1990). Mechanisms underlying the anisotropy of stereoscopic tilt perception. *Vision Research, 30,* 1781–1791. [PubMed]

Morrison, J. D., & Whiteside, T. C. (1984). Binocular cues in the perception of distance of a point source of light. *Perception, 13,* 555–566. [PubMed]

Ogle, K. N. (1964). *Researches in binocular vision.* New York: Hafner.

Ooi, T. L., Wu, B., & He, Z. J. (2006). Perceptual space in the dark affected by the intrinsic bias of the visual system. *Perception, 35,* 605–624. [PubMed]

Patla, A. E., Niechwiej, E., Racco, V., & Goodale, M. A. (2002). Understanding the contribution of binocular vision to the control of adaptive locomotion. *Experimental Brain Research, 142,* 551–561. [PubMed]

Pierce, B. J., Howard, I. P., & Feresin, C. (1998). Depth interactions between inclined and slanted surfaces in vertical and horizontal orientations. *Perception, 27,* 87–103. [PubMed]

Poom, L., Olsson, H., & Borjesson, E. (2007). Dissociations between slant-contrast and reversed slant-contrast. *Vision Research, 47,* 746–754. [PubMed]

Siderov, J., Harwerth, R. S., & Bedell, H. E. (1999). Stereopsis, cyclovergence and the backward tilt of the vertical horopter. *Vision Research, 39,* 1347–1357. [PubMed]

Tcheang, L., Gilson, S. J., & Glennerster, A. (2005). Systematic distortions of perceptual stability investigated using immersive virtual reality. *Vision Research, 45,* 2177–2189. [PubMed]

Tresilian, J. R., Mon-Williams, M., & Kelly, B. M. (1999). Increasing confidence in vergence as a cue to distance. *Proceedings of the Royal Society of London B: Biological Sciences, 266,* 39–44. [PubMed] [Article]

van Ee, R., Banks, M. S., & Backus, B. T. (1999). An analysis of binocular slant contrast. *Perception, 28,* 1121–1145. [PubMed]

Wann, J. P., Rushton, S., & Mon-Williams, M. (1995). Natural problems for stereoscopic depth perception in virtual environments. *Vision Research, 35,* 2731–2736. [PubMed]

Werner, H. (1937). Dynamics in binocular depth perception. *Psychological Monographs, 49,* 1–120.

Westheimer, G. (1979). The spatial sense of the eye. *Investigative Ophthalmology and Visual Science, 18,* 893–912. [PubMed] [Article]

Wilkie, R. M., & Wann, J. P. (2003). Eye-movements aid the control of locomotion. *Journal of Vision, 3*(11):3, 677–684, http://journalofvision.org/3/11/3/, doi:10.1167/3.11.3. [PubMed] [Article]

Wilkie, R. M., Wann, J. P., & Allison, R. S. (2008). Active gaze, visual look-ahead and locomotor control. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 1150–1164. [PubMed]

Willemsen, P., Colton, M. B., Creem-Regehr, S. H., & Thompson, W. B. (2009). The effects of head-mounted display mechanical properties and field of view on distance judgments in virtual environments. *ACM Transactions on Applied Perception, 6,* 1–14.

Wu, B., He, Z. J., & Ooi, T. L. (2007). Inaccurate representation of the ground surface beyond a texture boundary. *Perception, 36,* 703–721. [PubMed]

Wu, B., Ooi, T. L., & He, Z. J. (2004). Perceiving distance accurately by a directional process of integrating ground information. *Nature, 428,* 73–77. [PubMed]