Thresholds for stereo-slant discrimination between spatially separated targets are influenced mainly by visual and memory factors but not oculomotor instability

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Surface-slant variations can be sensed either simultaneously with steady fixation or sequentially with saccadic gaze shifts. Stereo-slant discrimination thresholds are affected by visual, oculomotor, and memory factors. We have investigated the effects of fixation strategy, target separation, and exposure duration on stereo-slant discrimination. With long exposure durations (734 ms), stereo-slant discrimination thresholds measured with simultaneous presentation of test and reference stimuli were lower with gaze shifts than without them when target separations exceeded 4 deg. Above 4-deg target separations, the benefits of improved disparity resolution with foveal gaze shifts outweighed the costs of oculomotor variability associated with saccades. With short exposure durations (167 ms), as target separation increased, stereo-slant discrimination thresholds measured without gaze shifts increased with both sequential and simultaneous stimulus presentations, whereas thresholds with gaze shifts remained constant. This indicates that oculomotor errors are not an important factor in stereo-slant discrimination. In contrast to stereo-slant thresholds, sequential stereo-depth thresholds between two dots, measured with gaze shifts, increased with target separation. Thus, oculomotor error increases with target separation, and it is an important factor in stereo-depth discrimination.

Keywords: stereopsis, slant discrimination, sequential, simultaneous, gaze shift, oculomotor, visual, memory loss

Introduction

Binocular disparity cues can be used to recover slant and variations of surface orientation of extended surfaces (Backus, Banks, van Ee, & Crowell, 1999; Ogle, 1956; Rogers & Bradshaw, 1995). When comparing slant of widely separated surface locations, only one location can be imaged on the fovea at a time and other locations are imaged in the retinal periphery. Two surface locations can be compared simultaneously with steady foveal fixation on one location or sequentially with alternate foveal gaze shifts between the two locations. It is not obvious which of these two fixation strategies will yield the lowest threshold.

The first goal of this study is to identify the minimum target separation for which thresholds for slant discrimination are lowered by gaze shifts between two targets. Prior studies of two-point stereo-depth discrimination demonstrate that thresholds measured with widely spaced targets are lower with foveal gaze shifts between targets than during steady fixation on one target when target separations were greater than approximately 2 deg (Ogle, 1956). Do gaze shifts also improve stereo-slant thresholds for widely separated targets?

It is not obvious whether gaze shifts would lower thresholds for stereo-slant discrimination measured with widely separated targets. The threshold is determined by a combination of visual, oculomotor, and temporal factors. First, memory loss and the usefulness of the gradient of relative disparity between edges (Gillam, Flagg & Finlay, 1984) are influenced by whether the targets are presented simultaneously or sequentially. Second, disparity resolution is influenced by whether the targets are presented in the fovea or in the periphery (McKee, Welch, Taylor, & Bowne, 1990). Third, the magnitude of oculomotor error is influenced by the amplitude of saccadic gaze shifts and these motor errors can contribute to errors of space perception (Becker, 1972; Bridgeman & Stark, 1979; Collewijn, Erkelens, & Steinman, 1988; Henson, 1979; Mack, 1970; Whipple & Wallach, 1978). The main goal here is to study the influence of these factors on stereo-slant discrimination. These factors and their influence under different viewing conditions are discussed extensively in the following section.

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Factors Affecting Thresholds for Slant Discrimination

Stereo-slant estimates of a planar surface are based on horizontal disparity subtended by the surface elements and the location of the surface relative to the head (Backus et al., 1999; Ogle, 1950). Here we will refer to slant about a vertical axis as "slant." Slant about a vertical axis can be produced by horizontal magnification of one ocular image (i.e., a horizontal size ratio [HSR]) between the two retinal images not equal to 1.0. This produces a horizontal gradient of horizontal disparity between the two images (Rogers & Bradshaw, 1993). By itself, the horizontal disparity gradient is ambiguous. The same horizontal disparity patterns can correspond to many different oculo-centric and head-centric slants, depending on their distance and azimuth. The horizontal disparity gradient is scaled for distance and azimuth to recover slant (Garding, Porrill, Mayhew, & Frisby, 1995).

Information about distance and azimuth can be derived from either vertical disparity (vertical size ratio [VSR]) or horizontal gradient of vertical disparity (Backus et al., 1999; Brenner, Smeets, & Landy, 2001; Gillam & Lawergren, 1983), or oculomotor correlates of version (ϕ) and horizontal vergence (μ) (Brenner & van Damme, 1998). Estimates of azimuth based on oculomotor signals use version eye position and are mainly used when there is little information about vertical disparities, such as with short-height targets (Backus et al., 1999). Vertical disparity was minimized in this study by using short height stimuli.

Disparity Resolution and Retinal Eccentricity

The binocular signal for surface slant stimuli is a horizontal gradient of relative disparity. The sensitivity to relative disparity between two points falls off with retinal eccentricity (Fendick & Westheimer, 1983). Thresholds vary from 5 arcsec at the fovea to approximately 60 arcsec at 10 deg retinal eccentricity. At the fovea, thresholds are thought to be limited by the variance in the response of spatial filters, which is relevant for position coding. At large retinal eccentricities, thresholds are thought to be limited by resolution of local sign (Weymouth, 1958) that is determined by spatial grain of the retina and the cortical magnification factor (Burbeck & Yap, 1990; Levi & Klein, 1990).

The Gradient of Relative Disparity Between Edges of Adjacent Targets

Slant discrimination can be based upon a comparison of slant estimates at two separate locations. In addition, slant discrimination between two surfaces can be based on the relative disparities between the edges of the two surfaces. Sensitivity to these relative disparities falls off as target separation increases (Ogle, 1956; Rady & Ishak, 1955; Shipley & Popp, 1972; Wright, 1951).

The difference between horizontal gradients of horizontal disparity subtended by the edges of our two surfaces is proportional to the difference in slant between the two surfaces. This gradient of relative edge disparities (Figure 1 and Figure 2) provides a cue for stereo-slant discrimination that has been shown to increase the accuracy and reduce response time of super-threshold slant estimation (Gillam et al., 1984). Slant estimates are reduced as separation increases vertically or in depth (Gillam & Blackburn, 1998). Presumably, separation in time would also impair the use of the gradient of relative disparities between edges of surfaces by preventing the simultaneous comparison of disparity at the two separated edges.

Oculomotor Factors

Gaze shifts improve resolution of retinal disparity by imaging targets on the fovea and the horopter where sensitivity to disparity is the highest (Badcock & Schor, 1985; Stevenson, Cormack, & Schor, 1989); however, they also introduce oculomotor errors from horizontal vergence and version uncertainty. Oculomotor errors could influence slant discrimination in several ways. As indicated by Equation 1, the accuracy of registered version (ϕ) and horizontal vergence (μ) during sequential gaze shifts can limit the accuracy of slant estimates (Banks & Backus, 1998).

$$Slant\ (S) = -\tan\left(\frac{1}{\mu} \times \ln(HSR) - \tan(\phi)\right) \qquad (1)$$

Uncertainty of sensed eye position associated with gaze shifts increases with saccade amplitude. For example, the thresholds for detecting changes in separation between the present and a previous direction of gaze equals 10% of the saccade amplitude (Becker, 1972; Bridgeman & Stark, 1979; Henson, 1979; Mack, 1970; Whipple & Wallach, 1978). The error is a combination of undershoots and variability that increase with saccade amplitude (Boucher, Groh, & Hughes, 2001). Horizontal vergence errors also increase with saccade amplitude. Horizontal vergence errors occur during both vertical and horizontal saccades (Collewijn et al., 1988; Enright, 1989) and they could elevate sequential stereo-depth thresholds.

Stereo-slant stimuli used in the current study could minimize the influence of both horizontal vergence and version errors on slant discrimination thresholds. Horizontal vergence error would not degrade disparity signals for either simultaneous or sequential stereo-slant estimates because each slant stimulus contains relative disparities that make up the horizontal disparity gradient. Horizontal vergence errors would add a constant disparity to the entire surface but the relative disparities making up the horizontal disparity gradient and HSR would be unaffected. Horizontal vergence errors would not add to differences between simultaneously presented disparities because it is common to binocular images seen simultaneously and it is cancelled in a presumed differencing process between absolute disparities (Westheimer, 1979a). Horizontal vergence errors could introduce small scaling errors of slanted surfaces that could potentially alter slant magnitudes perceived in sequential presentations when HSR values were not equal to 1.0. Slant scaling errors of the reference surface were minimized with our fronto-parallel reference surface (HSR=1.0) that was presented in the straight-ahead direction. Note that cyclo-vergence during vertical gaze shifts (Schor, Maxwell, & Graf, 2001) could introduce shear disparity but these are very small disparities for our viewing distance and do not interfere with estimating slant about a vertical axis.

Horizontal version errors produce uncertainty in azimuth estimates that could produce sequential stereo-slant errors (Equation 1). We have reduced the influence of version errors on slant discrimination by using stimuli that are aligned vertically in the straight-ahead direction. In a control experiment, we compared stereo-slant discrimination thresholds measured with gaze shifts between vertically and horizontally separated targets in order to determine if any oculomotor error was large enough to influence estimates of azimuth and stereo-slant.

Temporal Factors

The difference in stereo-slant discrimination thresholds measured with and without gaze shifts could also be affected by a temporal factor (memory loss). Foveal gaze shifts between widely spaced targets could improve the resolution of their disparities; however, gaze shifts also introduce time delays between sequential views of fixated targets. The onset asynchrony between views of sequentially fixated targets can be as brief as 300 ms. The normal latency for a saccade is 200 ms and the duration of the saccade can be up to 100 ms (Bahill, Bahill, Clark, & Stark, 1975). Saccadic gaze shifts are associated with elevated detection thresholds (saccadic suppression) (Breitmeyer & Ganz, 1976) that could elevate stereo thresholds. However, even when time delays between stereo stimuli are introduced artificially without saccades, and targets are presented within the foveal area, sequential stereo-depth thresholds are 3 to 4 times higher than simultaneous stereo-depth thresholds (Enright, 1991a; Enright, 1991b; Kumar & Glaser, 1994; McKee et al., 1990; Westheimer, 1979a). Memory loss (Foley, 1976), and possibly temporal masking for brief stimulus onset asynchronies (Butler & Westheimer, 1978) have both been considered as contributing factors to the elevation of the sequential stereo-depth threshold.

Current Experiments

Foveal gaze shifts improve disparity resolution from peripheral to foveal levels (McKee et al., 1990), but gaze shifts could also increase oculomotor errors associated with saccadic gaze shifts (Becker, 1972; Bridgeman & Stark, 1979; Collewijn et al., 1988; Henson, 1979; Mack, 1970; Whipple & Wallach, 1978). The influence of visual and oculomotor factors on slant discrimination thresholds changes with target separation. The current investigation explores how saccadic gaze shifts affect stereo-slant discrimination thresholds between spatially separated targets. Slant discrimination thresholds were measured as a function of vertical separation between the test and reference patches. We have demonstrated the benefits of gaze shifts by comparing stereo-slant discrimination between two surfaces viewed simultaneously for a long duration (734 ms) either with steady fixation on the reference target or with gaze shifts between targets.

We have also compared thresholds measured with short durations (167 ms) with targets presented simultaneously with steady fixation and sequentially with either steady fixation or saccadic gaze shifts between the two targets. These experiments included different spatial, temporal, and oculomotor conditions that might influence slant discrimination thresholds. We found that at large separations, thresholds measured with gaze shifts were lower than those measured with steady fixation, and that the threshold for sequential target presentation measured with gaze shifts was independent of target separation, suggesting that in our experiment, oculomotor errors did not have an important influence on thresholds for stereo-slant discrimination.

More horizontal version errors would be expected to accompany horizontal than vertical saccadic gaze shifts. We investigated the influence of the horizontal version errors associated with saccades by comparing slant discrimination thresholds for the sequential condition measured with vertical and horizontal saccades.

Horizontal vergence errors are thought to influence sequential stereo-depth thresholds (Westheimer, 1979a). Stereo-depth thresholds increase with target separation when measured with saccadic gaze shifts between targets (Enright, 1991b; Ogle, 1956). This increase could be attributed to an increase of horizontal vergence errors with saccade amplitude. Assuming this interpretation is correct, we compared sequential stereo-depth with sequential stereo-slant to illustrate that horizontal vergence errors affect stereo slant and depth estimates differently.

General Methods

Display and Stimuli

The stimuli were displayed on a 20-in. monochrome monitor (Monoray Model M20ECD5RE; Clinton Electronics, Loves Park, IL, USA) at 120-Hz non-interlaced frame rate with 1024 by 768 pixel resolution. This monitor had a fast DP 104 CRT phosphor that decays to 0.1% peak in 0.6 ms with a burn resistant property. The fast phosphor decay is critical for minimizing the cross talk between images presented to left and right eyes because we were using the same screen area with shutter glasses to generate stereograms. Video images were controlled using Visual Stimulus Generators (VSG) 2/3 graphics card (Cambridge Research Systems, Kent, England) in a host Pentium computer. The images were corrected for any screen pincushion and prismatic distortions at the 57.3-cm test distance using a grid-loom calibration method (Backus et al., 1999). At that viewing distance, there are 29 pixels per degree horizontally. All stimuli were viewed through 120-Hz Ferro-shutter optics (model FE-1 ferroelectric shutter goggle; Cambridge Research Systems, Kent, England). Each eye viewed stimuli at 60 Hz with no discernable flicker.

The simulated planes consisted of elliptical patches of sparse, randomly positioned dots to minimize perspective and texture cues for surface orientation (e.g., Figure 1). The elliptical patches had a variable aspect ratio averaging 0.19. Average height was 1.5 deg and width was 8 deg. A stimulus height of 1.5 deg has been shown to contain few if any effective vertical disparity cues for providing information about target distance or azimuth (Backus et al., 1999). The 8 deg-stimulus width provided a large enough area to stimulate slant perception with horizontal disparity information. Each patch contained about 90 irregularly spaced dots. Sub-pixel resolution was obtained by anti-aliasing each dot (Klein, Hu, & Carney, 1996). Each dot was a luminance Gaussian distribution with a sigma of 2/3 pixels. The peak luminance was 4.2 cd/m^2 at the screen when viewed through the Ferro-shutters.

Horizontally slanted stimuli were obtained by applying a horizontal magnification of one eye's image. The disparity gradients were always consistent within a plane rotated about a vertical axis (tilt axis = 0.0 degree). At the 57.3-cm viewing distance for a 6-cm interpupillary distance, a horizontal size ratio (HSR) of 1.01 corresponds to a slant of approximately 5 deg. Test planes were compared to a fronto-parallel reference plane in the straight-ahead position.

Figure 2 shows the spatial (upper panel) and temporal (lower panel) configuration of the stimuli used in this experiment. The stimuli contained reference and test planes separated vertically with the test located above the reference. The fixation point was at the center of the reference plane. Vertical separation is defined as the distance between the center of the reference and the center of the test patches. We refer to this vertical separation as the eccentricity of the test stimuli. Vertical separations were 2, 4, 8, or 12 deg. In order to reduce the impact of off-horopter disparities on the sensitivity to stereo-slant stimuli, the axis of slant was parallel to the empirical vertical horopter of each subject. The vertical horopter was measured with vertical nonius lines (0.25 deg long) presented in the midsagittal plane at elevations from 0 to 4 deg above and below the central fixation target. Standing horizontal disparities between test and reference surfaces have been shown to produce underestimates of slant magnitude (Gillam & Blackburn, 1998). Placement of test and reference targets along the vertical horopter ensured that there were no standing horizontal disparity differences between surfaces and that their axes of slant were coplanar.

Figure 2 (bottom panel) shows the time course of the stimuli. The reference and the target stimuli were presented either simultaneously (left panel) or sequentially (right panel) with an inter-stimulus interval (ISI) of 400 ms. This ISI is longer than the sum of the latency (200 ms) and maximum duration (100 ms) of saccadic gaze shifts. Reference and test targets had the same stimulus duration of 167 ms or 734 ms.

The experiment was conducted in complete darkness to eliminate visibility of the room, edges of the monitor and facial features as frames of reference. The subject's head position was fixed by means of a bite board and headrest to align the eyes with the calibrated view-points.

Figure 1. A stereogram of the dichoptic slant stimulus configuration for test and reference planes. The bottom dichoptic pair of patches illustrates the reference with 0-deg slant. The top dichoptic pair of patches illustrates the test that was presented at various slants by varying its horizontal size ratio. Each patch had an elliptical shape with an 8-deg horizontal visual angle and 1.5-deg vertical angle filled with sparse randomly positioned dots

Procedure and Data Analysis

Stimuli were presented according to the method of constant stimuli, with a two-alternative forced-choice response procedure. In each trial, the magnification of the test was selected randomly from 1 of 9 levels, and each level was presented 6 times in a given session. Each stimulus had a different random dot pattern. Before each trial, subjects monitored the accuracy of their horizontal vergence by using two vertical nonius markers located above and below the fixation dot. When the nonius lines appeared aligned, the subject initiated a trial by pressing a button to replace the fixation pattern with a short-duration stimulus. Reference (fronto- parallel) and test patches with varying amounts of slant were presented either simultaneously or sequentially at various retinal eccentricities with respect to the fixation spot (Figure 2). With these two stimulus presentations, subjects were instructed either to make a saccadic gaze shift from the center of the reference to the center of the test target in order to foveate both patches sequentially, or to hold fixation on the center dot of the lower reference patch. The two stimulus presentations and eye-movement conditions resulted in four combinations of experimental conditions: simultaneous presentation without or with a gaze shift, and sequential presentation without or with a gaze shift. For simplicity, we refer to these conditions as simultaneous *with* gaze shift, simultaneous *without* gaze shift, sequential *with* gaze shift, and sequential *without* gaze shift. The subject's task was to indicate whether the test plane was slanted left side farther away than the reference.

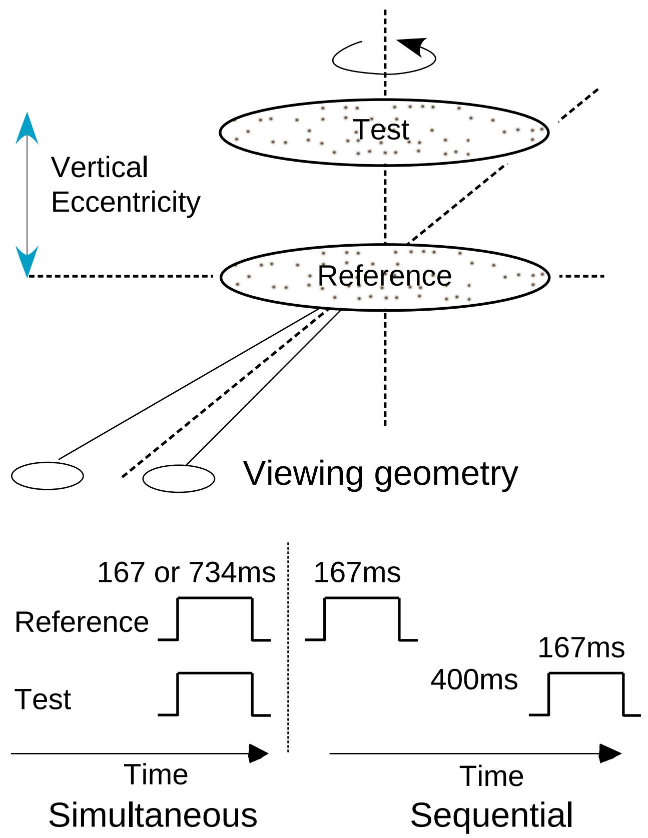

Figure 2. Spatial and temporal configuration of the stimuli. Spatial configuration: the center of the reference patch was always positioned at the fixation point. The slanted test surface was placed above the reference at various vertical eccentricities ranging from 2 to 12 deg. Vertical eccentricity was measured as the distance between the centers of the two patches. All the surfaces were placed on the subject's vertical horopter. Temporal configuration. Simultaneous: both appear at the same time with durations of 167 or 734 ms. Sequential: the reference was followed by the test; each presented for 167 ms, with a 400-ms inter-stimulus interval. The subject either made vertical saccadic gaze shifts between test and reference targets or maintained fixation at the center of the lower reference target.

Percentage of correct responses from at least six sessions was plotted as a function of HSR for each experiment condition, and was fit (maximum likelihood) with a psychometric function (cumulative Gaussian) in order to estimate a threshold or just-noticeable difference (JND). The JND equaled the SD of the cumulative Gaussian. The JND is half of the difference between the values of the independent variable corresponding to 16% and 84% of correct performance (d' = 1). SEs were estimated by performing Monte-Carlo simulations of the original data sets (i.e., bootstrap replications). Each experimental session began with 10-20 practice trials. Three observers (ZZ, CS, and PI) were tested. PI was naïve as to the purpose of the experiments.

Experiment 1: Can Gaze Shifts Improve the Stereo-Slant Discrimination Between Spatially Separated Targets?

There are two possible viewing strategies for spatially separated targets under naturally viewing conditions. Either the targets can be viewed sequentially in time with a foveal gaze shift between them, or they can be viewed simultaneously with steady foveal fixation of one target and a peripheral view of the other target. With small target separations, both surface locations are near the fovea and thresholds measured with and without gaze shifts are either equal or the threshold with gaze shifts could be elevated by oculomotor errors. Ideally, the optimal fixation strategy with small target separations would be to maintain foveal alignment at one target location. With large target separations, reduced disparity resolution in the retinal periphery could elevate thresholds more than the oculomotor errors associated with foveal gaze shifts. Then, the optimal strategy with large target separations would be to make foveal gaze shifts between targets.

This experiment compared stereo-slant discrimination thresholds, measured with or without gaze shifts between the simultaneously presented reference and test target, as a function of target separations. We predict that the gaze shifts would benefit slant discrimination at large target separations but not at small ones.

Methods

The test and reference stimuli were presented simultaneously for 734 ms, which provided enough time to make one saccade from the reference to the test. Subjects either maintained fixation on the reference target (without gaze shift condition), or made a saccade from the reference to the test target (gaze shift condition). Four vertical target separations were used (2, 4, 8, and 12 deg).

Results and Discussion

Stereo-slant discrimination thresholds, measured with or without gaze shifts as a function of target separation, are plotted for three subjects in Figure 3. We fit the results with quadratic functions. Both thresholds increased with target separation and thresholds increased more abruptly for the without gaze shift condition than the with gaze shift condition.

The increase of thresholds with target separation in the simultaneous without gaze shift condition could be due to reduced disparity resolution in the periphery. Gaze shifts between the reference and test decreased the thresholds at large vertical separations, possibly by improving the disparity resolution of the test stimulus (McKee et al., 1990). Even though the gaze shifts placed both the reference and test target onto the fovea, the thresholds for the simultaneous with gaze shift condition still rose with target separation. The increase of stereo-slant threshold with target separation could have resulted from a transition in viewing strategy from a simultaneous comparison of the test and reference at small target separations, when both were imaged near the foveal region, to sequential foveal views of the two targets at larger target separations. Several factors could contribute to the threshold elevation with target separation in the gaze shift condition, including oculomotor errors, memory loss and reduced use of the gradient of relative disparity between adjacent edges of the two targets.

Gaze shifts between large target separations could introduce oculomotor errors that have both version and horizontal vergence components, both of which have been shown to increase with saccade amplitude (Becker, 1972; Bridgeman & Stark, 1979; Collewijn et al., 1988; Henson, 1979; Mack, 1970; Whipple & Wallach, 1978). Oculomotor errors that were unregistered could add variability to the mapping of disparity to slant estimates.

Memory loss is a temporal factor that would elevate thresholds if viewing strategy changed from simultaneous comparisons during steady fixation to sequential ones with gaze shifts. Even though test and reference stimuli were presented simultaneously, memory loss could occur with asynchronous foveal views, before and after gaze shifts, when the separation between test and reference targets was large.

Simultaneous comparison of the gradient of relative disparities between adjacent edges of two targets (Gillam et al., 1984) might become less effective as target separation increased and with the introduction of a time delay between foveal views of the reference and test stimulus in the gaze shift condition.

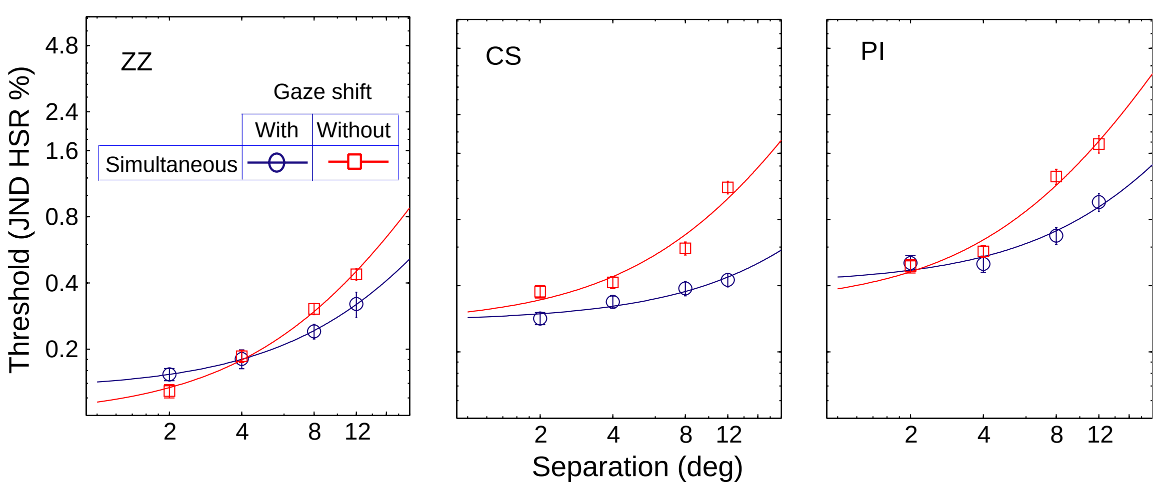

Figure 3. Stereo-slant discrimination thresholds measured with (open circles) or without (open square) gaze shifts as a function of target separation. Both thresholds increase with target separation, and thresholds for the without gaze shift condition increased with target separation more abruptly than for the with gaze shift condition,

Experiment 2: Factors That Affect Stereo-Slant Discrimination Between Vertically Separated Targets

In the first experiment, we concluded that the gaze shifts could improve stereo-slant discrimination at large vertical target separations (> 4 deg). We also observed that thresholds for the simultaneous with gaze shift condition increased with target separation.

In Experiment 2, three conditions were used to evaluate the contribution of oculomotor errors, memory loss, and edge comparison to stereo-slant threshold elevation. The three conditions included sequential presentation of reference and test slant stimuli, either with or without gaze shifts, and simultaneous presentation without gaze shifts. All three conditions varied vertical target separation and had a short stimulus duration (167 ms).

The first condition (sequential with gaze shift) quantified the influence of oculomotor errors on thresholds for sequential slant discrimination. In this condition, oculomotor errors are the main factor that could change with amplitude of gaze shifts. Because targets were presented sequentially, with a fixed ISI (400 ms), memory loss and disparity resolution were independent of target separation, and asynchronous stimulation minimized the use of the gradient of relative disparity information between the adjacent target edges. We predict that if oculomotor errors increase with saccade amplitude, then the threshold for the sequential with gaze shift condition could increase with target separation.

The second and third conditions compared sequential and simultaneous slant discrimination, both without gaze shifts, to reveal the combined influence of (1) memory loss, (2) the gradient of relative edge disparities, and (3) the resolution of disparity in the periphery. The resolution of disparity decreases with target separation equally in both the simultaneous and the sequential conditions.

Memory loss of target information, that was independent of target separation, could be introduced by the time delay (400 ms) between stimuli in the sequential without gaze shift condition (Foley, 1976). Memory loss would be minimal in the simultaneous condition. We predict that if temporal delay only influences memory loss, then any difference between thresholds for the sequential and simultaneous conditions measured without gaze shifts would be constant at all target separations.

The gradient of relative disparity between target edges is more useful for slant discrimination in simultaneous condition than in the sequential condition. If the use of the gradient of relative disparity between target edges were reduced as target separation increased, then the difference in simultaneous and sequential thresholds in the without gaze shift conditions would be larger at small than large target separations.

Methods

Sequential With Gaze Shift Condition

The reference and test stimuli were each presented sequentially for 167 ms with a 400-ms ISI and subjects made a saccade from the reference to the test target. This ISI was chosen to approximate the sum of the normal saccade latency (250 ms) and the longest saccade duration (100 ms) that occur with large saccades.

Sequential Without Gaze Shift Condition

The reference and test targets were each presented for 167 ms with a 400-ms ISI while fixation was held on the center location of the reference target.

Simultaneous Without Gaze Shift Condition

The reference and test stimuli were presented simultaneously for 167 ms while fixation was held on the center location of the reference target. Targets were separated vertically with the test elevated above the reference at the same separations as used in Experiment 1.

Results and Discussion

Stereo-slant discrimination thresholds, measured with different vertical separations between the test and reference stimuli, are plotted for three subjects in Figure 4. Data are shown for the three conditions: sequential with a gaze shift (filled circles) or without a gaze shift (open circles), and simultaneous without a gaze shift (open squares).

Sequential With Gaze Shift Condition

As separation increased, thresholds remained almost constant with vertical separation. The fitted slopes did not differ significantly from zero ($p > .05$). The independence of thresholds on target separation suggests that oculomotor errors associated with vertical saccadic gaze shifts had little if any effect on the sequential slant discrimination threshold. Vertical disparity could not be used to estimate distance and azimuth, which is critical to the slant estimation, because the target was too narrow to provide adequate vertical disparity information.

In contrast to the two without gaze shift conditions, the thresholds for the sequential with gaze shift condition were independent of target separation. This constant threshold could be explained in several ways. First, there might not be much horizontal version errors associated with vertical saccades. Second there are horizontal version errors, but they do not vary with saccade amplitude. Third, there is not much error of horizontal vergence associated with vertical saccades. Fourth, there are horizontal vergence errors, but they are independent of

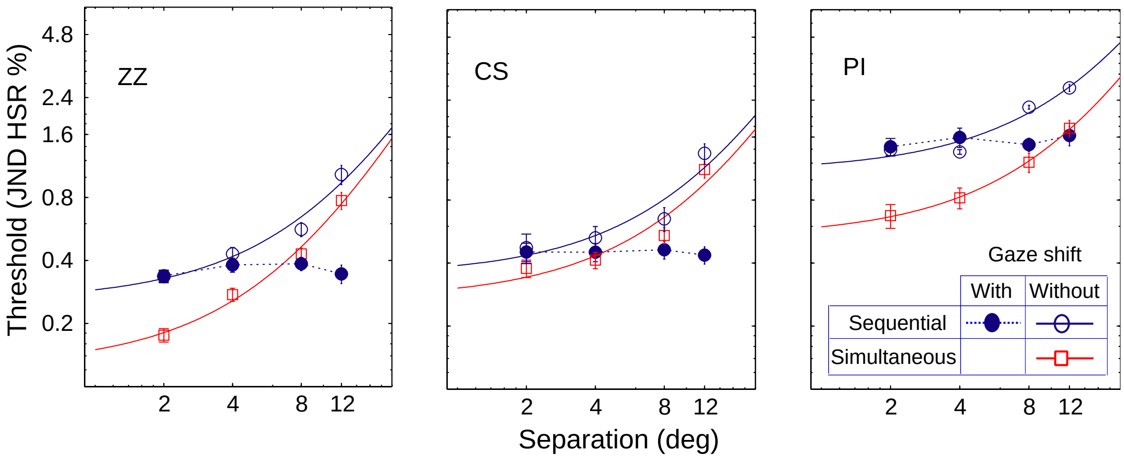

Figure 4. Stereo-slant discrimination thresholds are plotted as a function of vertical target separation for three conditions, including: sequential presentation with or without gaze shifts (filled and open circles), and simultaneous presentation without gaze shifts (open squares). For the sequential with gaze shift condition, thresholds were constant at all target separations, but they increased with target separation for the other two without-gaze shift conditions. In the without-gaze shift conditions, thresholds were higher at all target separations for the sequential than the simultaneous target presentations.

saccade amplitude. Vergence errors would only change the magnitude of slant of a non-fronto parallel surface. However, when the fronto-parallel reference surface is perceived as slanted due to errors in azimuth, then vergence errors could have an impact. Vergence errors could also affect slant threshold because of the low resolution of disparity information off the horoptor. These four possibilities are addressed in Experiments 3 and 4.

Simultaneous and Sequential Without Gaze Shift Conditions

Thresholds were lower at all vertical target separations for the simultaneous (open squares) than the sequential presentations (open circles) of reference and test stimuli. Two factors differed in the simultaneous and sequential without gaze shift conditions. One factor was the memory loss introduced by 400-ms ISI between test and reference stimuli in the sequential condition. Memory loss could introduce a uniform threshold elevation for the sequential condition across vertical target separations. The other factor was the more effective use of the gradient of relative disparity information between the test and reference edges in the simultaneous condition (Gillam et al., 1984). At small target separation, the reduced use of the gradient of relative disparity information in the sequential condition might introduce an additional elevation of the sequential above the simultaneous threshold.

We fit the results from the sequential and simultaneous without gaze shift conditions in Figure 4 with quadratic functions. The curves illustrated that the difference between these two conditions was not constant. Figure 5 illustrates a schematic of uniform and nonuniform components of the threshold elevation of the sequential without gaze shift condition over the simultaneous one. The dashed line is a normalization of the sequential fit to coincide with the simultaneous fit at the largest target separation. The divergence of the dashed and solid curves at small separations could result from the reduced use of the gradient of relative disparity information at target edges in the sequential condition.

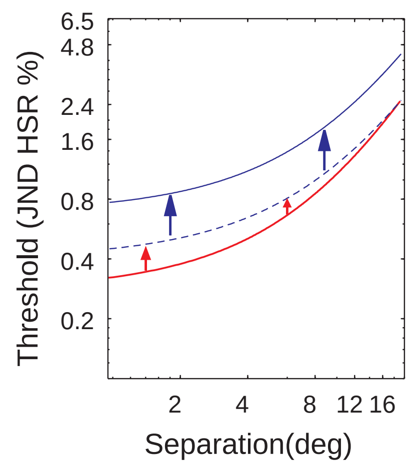

Figure 5. Schematic summary that illustrates two possible factors that would differ between the sequential and simultaneous threshold curves shown in Figure 4. The lower red and higher blue solid line represent the simultaneous and sequential without gaze shift threshold curves. Two factors could contribute to the elevation of thresholds for the sequential condition. One is the memory loss that elevates thresholds uniformly from dashed blue line to the solid blue line (indicated by the blue arrows). The other is the use of the gradient of relative disparity information between edges, which decreases as target separation increases in simultaneous condition, and results in the non-uniform elevation in thresholds for the sequential condition (from red solid curve to the dashed blue curve, indicated by the red arrows).

We concluded from Figure 4 and Figure 5 that thresholds for each subject were affected differently by memory loss and the gradient of relative disparity. ZZ was affected more by the gradient of relative disparity in simultaneous condition, and less by the memory loss in sequential condition. CS was affected little by either the gradient of relative disparity in simultaneous condition or the memory loss in sequential condition. PI was affected less by the gradient of relative disparity in simultaneous condition, and more by the memory loss in sequential condition.

Experiment 3: Sequential Slant Discrimination With Horizontal Gaze Shifts

The sequential with gaze shift condition in Experiment 2 tested the influence of oculomotor errors associated with vertical gaze shifts on slant discrimination. The results suggested that the oculomotor errors had no significant effect on the threshold. However, horizontal saccades might introduce more horizontal version errors and have therefore a greater influence on slant discrimination thresholds than would vertical gaze shifts.

We used short height stimuli (1.5 deg) to minimize the use of vertical disparity cues to azimuth so that the azimuth estimation depended mainly on horizontal version information (Backus et al., 1999). Experiment 2 minimized the effects of horizontal version errors on slant discrimination by separating the reference and test targets vertically. Experiment 3 was designed to reveal the affects of horizontal version errors on sequential slant discrimination by making saccades between horizontally separated targets. Assuming that horizontal version errors increase with saccade amplitude, we predict that azimuth signals and stereo-slant thresholds would be affected more by errors associated with horizontal than vertical gaze shifts and that the thresholds would increase with saccade amplitude.

Methods

Sequential stereo-slant thresholds measured with horizontal gaze shifts were compared to thresholds measured with vertical gaze shifts in Experiment 2. Reference and test targets were each presented for 167 ms with a 400-ms ISI. The test stimulus was 2 deg above the reference and was displaced horizontally along a virtual fronto-parallel plane with 4 separations (2-12 deg). The slant discrimination was relative to fronto-parallel plane and slant was specified in head-centric coordinates.

Results and Discussion

Figure 6 compares the sequential stereo-slant discrimination thresholds measured with vertical and horizontal gaze shifts. Thresholds were similar for the vertical (filled circles) and horizontal (open squares) gaze shift conditions. Similar to the vertical gaze shift condition, the fitted slopes for each subject were not significantly different from zero ($p > .05$) for horizontal gaze shift. The similar results for the two saccadic conditions indicate that the variance of oculomotor signals for azimuth had little affect on stereo-slant estimates. Either this is because the horizontal version error is small in comparison to other error sources that determine threshold, or it is because version errors do not increase with saccade amplitude. However, prior studies (Becker, 1972; Boucher et al., 2001; Bridgeman & Stark, 1979; Henson, 1979; Mack, 1970; Whipple & Wallach, 1978) suggest that horizontal version errors do increase with saccade amplitude.

It is surprising that gaze shifts had so little influence on slant discrimination thresholds at large horizontal

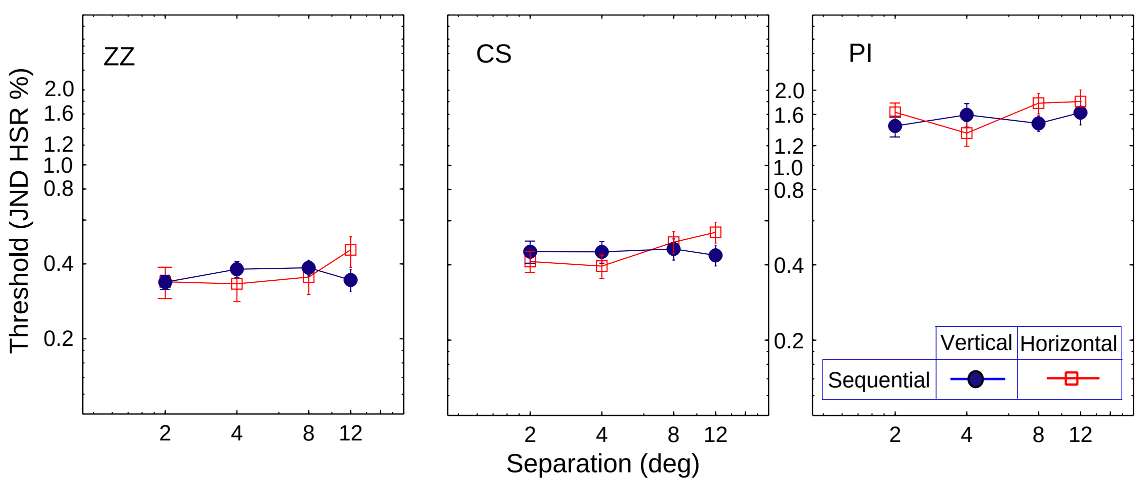

Figure 6. A comparison of stereo-slant discrimination thresholds measured with either a horizontal or vertical gaze shift during sequential target presentations. The reference and test stimuli were presented sequentially with a 400-ms ISI. Results for the vertical and horizontal gaze shifts are similar.

target separations given that sequential stereo-depth thresholds, measured with gaze shifts, have been observed to rise with target separation (Enright, 1991b; Ogle, 1956). It has been argued that the elevation for sequential stereo-depth is caused by horizontal vergence errors that introduce noise into absolute disparity signals (McKee et al., 1990; Westheimer, 1979b). In addition, horizontal version and vergence errors could both potentially produce errors in distance information needed to scale stereo-depth. Although we tried to minimize the influence of oculomotor errors, we didn't expect that we fully succeeded. Slant estimates are less influenced by oculomotor errors than is stereo-depth, and in the next experiment (4), we measured stereo-depth thresholds to test this assertion. It is possible that the subjects in this experiment had little variation of horizontal vergence with vertical saccades or that their horizontal vergence errors were independent of saccade amplitude.

Experiment 4: Stereo-Depth Discrimination Thresholds *With* Vertical Gaze Shifts

Indeed, if subjects in our experiment had little variation of horizontal vergence error with saccade amplitude, then we would predict that sequential stereo-depth thresholds measured with gaze shifts would also be independent of target separation. We have argued that small amounts of horizontal vergence errors, that are thought to elevate sequential stereo-depth thresholds, do not elevate sequential stereo-slant discrimination thresholds because they are based upon disparity gradient information within the test stimulus. Estimates of stereo-depth between two points rely exclusively upon differences in absolute disparities. The difference in two absolute disparities subtended by the two dots is believed to be influenced by horizontal vergence errors when the absolute disparities are presented sequentially (McKee et al., 1990; Westheimer, 1979b). Prior investigations of sequential stereo-depth discrimination, that allowed subjects to make saccades between targets, observed that thresholds increased with target separation (Enright, 1991b; Ogle, 1956). The increase of sequential stereo-depth thresholds with target separation, measured with gaze shifts, could result from an increase in the amplitude of horizontal vergence errors with saccade amplitude (Collewijn et al., 1988; Enright, 1989). Prior studies of sequential stereopsis (Enright, 1991a, 1991b; Ogle, 1956) were conducted with simultaneous presentation of test and reference stimuli that were viewed with alternating foveal gaze shifts. The elevation of sequential stereo-depth thresholds with increasing target separations could be related either to the reduced disparity resolution in the retinal periphery during any given fixation, or to an increase of oculomotor errors as saccade amplitude increased. In this investigation, we have eliminated the first possibility by presenting targets sequentially so that they were only visible at the fovea and not in the retinal periphery. With alternating stimulus presentations, any influence of target separation would be limited to oculomotor errors associated with saccades.

The goal of this experiment was to confirm Ogle (1956) and Enright's (1991a) observation of elevated sequential stereo-depth thresholds when the targets were presented sequentially and subjects made gaze shifts between targets. Here, we make a direct comparison between sequential stereo-depth and sequential stereo-slant discrimination, both measured with vertical gaze shifts as a function of target separation, to determine if horizontal vergence errors might have a bigger effect on the sequential stereo-depth task than on the sequential stereo-slant task.

Based on the results of Experiment 3, we assume that vertical version has a minimal effect on estimates of azimuth, and the main influence of vertical saccades on sequential stereo-depth thresholds would be to introduce horizontal vergence errors (Collewijn et al., 1988; Enright, 1989). We predict that the stereo-depth threshold would increase with target separation (saccade amplitude) if the horizontal vergence errors associated with vertical gaze shift increased with the saccade amplitude.

Methods

Stereo-depth thresholds were measured with gaze shifts between two vertically separated and sequentially presented single-dot stimuli. The results were compared to the stereo-slant thresholds measured in the sequential with gaze shift condition in Experiment 2. The same subjects were used as in Experiment 3; they showed little or no change in sequential stereo-slant thresholds with gaze shifts. The methods in this experiment were analogous to the slant discrimination experiment, except here we used reference and test stimuli, each composed of a single dot instead of a plane composed of many dots. The reference and test dots were presented sequentially for 167 ms each with a 400-ms ISI, and subjects made a vertical saccadic gaze shift between them. The subject's task was to judge whether the upper test dot was farther or nearer than the lower reference dot. The vertical separation between the dots was varied from 2-12 deg. Subject PI could not perform the task with a target separation greater than 4 deg because at large separations, stimuli that were below his stereo-depth threshold appeared diplopic.

Results and Discussion

Figure 7 plots stereo-depth discrimination thresholds (open circle) measured at different vertical separations between two dots with a saccadic gaze shift between them.

For comparison, the sequential stereo-slant thresholds (filled circles) measured with vertical gaze shifts in Experiment 2 were transformed into the equivalent relative disparity values between the lateral edges of the slant stimulus and the fronto-parallel plane. These estimates are based on the largest relative disparity that might determine threshold, however slant thresholds could have been determined by lower relative disparity estimates that corresponded to disparities closer to the central fixation point. These estimated disparity thresholds for slant discrimination are plotted as filled symbols in Figure 7 below the stereo-depth thresholds.

Unlike the results for the sequential stereo-slant condition with gaze shifts (filled circles), sequential stereo-depth thresholds (open circles) increased with target separation, rather than remaining constant. The increase of the sequential stereo-depth threshold with target separation suggests that the horizontal vergence error amplitude does increase with the magnitude of gaze shifts, and it is mainly responsible for the increase of stereo-depth threshold with target separation. The minimal effect of oculomotor errors on slant discrimination threshold could be attributed to the presence of relative disparities contained in both the test and reference slant stimuli that make stereo-slant less sensitive to oculomotor errors than is stereo-depth.

Discussion

Do Gaze Shifts Lower Thresholds for Stereo-slant Discrimination?

In Experiment 1, reference and test stimuli were presented simultaneously for a long duration (734 ms), and subjects either made a saccadic gaze shift between them or maintained fixation on the reference. Results showed that stereo-slant discrimination thresholds increased more abruptly with target separation in the without gaze shift than in the with gaze shift condition. Gaze shifts improved slant discrimination thresholds for target separations greater than 4 deg (Figure 3).

The increased thresholds with target separation in simultaneous without gaze shifts condition could be due to reduced disparity resolution in the periphery. Gaze shifts between the reference and test decreased the thresholds at large vertical separations by improving the disparity resolution of the test stimulus (McKee et al., 1990). Interestingly, even though the gaze shifts placed both the reference and test target onto fovea, the thresholds for simultaneous with gaze shifts still rose with target separation.

The increase of stereo-slant threshold with target separation observed for the simultaneous with gaze shift condition in Experiment 1 could have resulted from a transition in viewing strategy from simultaneous comparison of the test and reference at small target separations, when both were imaged near the foveal region, to sequential foveal views of the two targets at larger target separations.

An alternative explanation for the rise in stereo-slant thresholds with target separation in the with gaze shift condition is that subjects did not compare the sequential foveal views, but instead they tried to make simultaneous comparisons of the test and reference target following each saccade. If this alternative hypothesis were true, then the thresholds for both with and without gaze shift conditions would be identical at all the target separations. However, our results demonstrate that stereo-slant discrimination thresholds improved with gaze shifts at large target separations compared to the without gaze shift condition (> 4 deg).

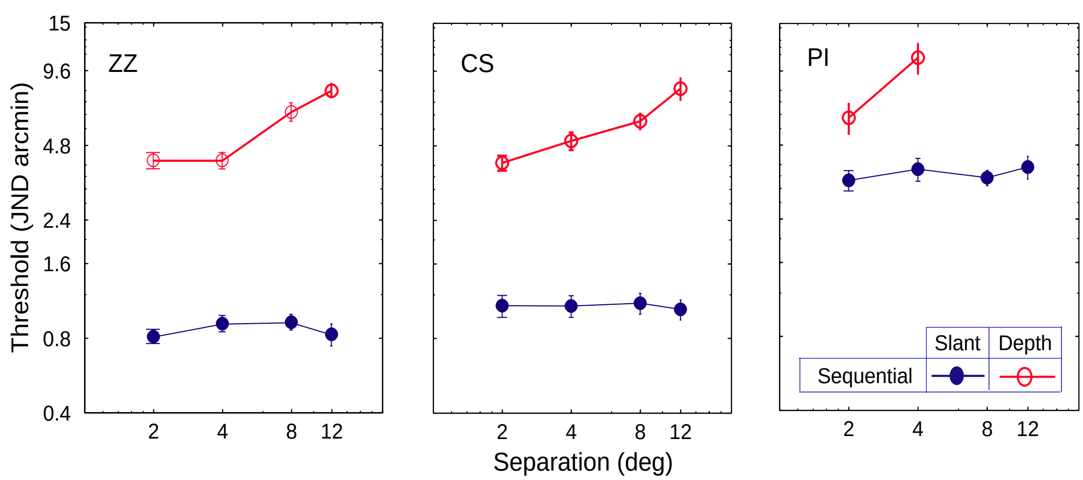

Figure 7. A comparison of stereo-slant (filled circles) and stereo-depth (open circles) thresholds measured with gaze shifts during the sequential presentation of reference and test stimuli. Stereo-slant thresholds were converted to units of disparity. Differences in the stereo-slant and stereo-depth threshold suggest that horizontal vergence errors appear to increase with saccade amplitude, and they have a greater influence on stereo-depth thresholds than on stereo-slant thresholds.

Factors Influencing Thresholds for Simultaneous and Sequential Slant Discrimination

We have identified several factors that might affect stereo-slant discrimination either with or without gaze shifts including (1) resolution of disparity that falls off with retinal eccentricity, (2) use of the gradient of relative disparity between adjacent target edges that decrease as the separation of targets increase in time and space, (3) memory loss that was introduced as viewing strategy changed from simultaneous to sequential view, and (4) oculomotor variability that increases with saccade amplitude. The influence of retinal eccentricity on disparity resolution was quantified by the sequential without gaze shift condition in Experiment 2. Combined effects of memory loss and gradient of relative disparity between abutting target edges was examined by comparing the results of the simultaneous and sequential conditions without gaze shifts in Experiment 2. There was less memory loss and the gradient of relative disparity was more useful in the simultaneous than sequential condition. The possible influence of oculomotor version errors was tested by comparing thresholds for the sequential with vertical gaze shift condition in Experiment 2 and the sequential with horizontal gaze shift condition in Experiment 3. The possible involvement of horizontal vergence errors was tested in Experiment 4 by comparing thresholds for sequential stereo-depth and sequential stereo-slant discrimination, both measured with vertical gaze shifts between targets as a function of target separation.

Disparity Resolution and Retinal Eccentricity

Stereo-slant thresholds in Experiment 2 increased with vertical target separation for both simultaneous and sequential without-gaze shift conditions. This trend resembles the increase of simultaneous and sequential stereo-depth discrimination thresholds with target separation (McKee et al., 1990).

For the constant fixation condition, two factors affect the stereo-slant thresholds when separation between the two targets is varied. First, the sensitivity to the disparity gradient within a surface, which is computed from the differences in absolute disparities subtended by texture elements, falls off with retinal eccentricity (Fendick & Westheimer, 1983). Second, separation between targets reduces sensitivity to the relative disparities between the adjacent edges of the two surfaces (Gillam et al., 1984). Similarly, sensitivity to disparity between two points falls off as target separation increases (Ogle, 1956; Rady & Ishak, 1955; Shipley & Popp, 1972; Wright, 1951). Oculomotor errors did not vary with target separation because no saccadic gaze shifts were allowed. Temporal factors were constant because the time delay was constant. Therefore, the effect of retinal eccentricity on disparity resolution can be quantified in the sequential without gaze shift condition (Experiment 2), assuming that the gradient of relative disparity between target edges is only useful when the targets are both present at the same time (i.e., not sequentially).

The effect of target separation on disparity resolution is largest for ZZ and smallest for PI. Threshold increased by 3-fold for ZZ, 2.8-fold for CS and 2-fold for PI when target separation increased form 2-to-12 deg (Figure 4). These values are similar to the result of Fendick & Westheimer (1983), in which they found a 3-to-4-fold increase in stereo threshold measured from 2.5-to-10-deg target separation (their Figure 5). They measured stereo-depth discrimination with both test and reference targets presented at the same retinal eccentricity.

There are several factors that could have influenced disparity sensitivity with retinal eccentricity. At the fovea, the variability in the responses of the spatial filters is thought to determine disparity resolution, and at larger eccentricities, the coarse spatial grain of the peripheral retina and the cortical magnification factor could both affect disparity resolution (Burbeck & Yap, 1990; Levi & Klein, 1990; McKee et al., 1990).

Effects of Temporal Asynchrony: Memory Loss and Reduced Use of the Gradient of Relative Disparity Between Edges

In Experiment 2, thresholds without gaze shifts were lower for simultaneous (open squares) than sequential presentations (open circles) of reference and test stimuli (Figure 4), and both thresholds increased with target separation. The difference between thresholds for these two conditions was accounted for by two factors, both related to the temporal delay between the presentation of the reference and test stimulus. One factor was the memory loss in sequential condition that would be expected to elevate the thresholds uniformly across all target separations. The other factor was due to the more effective use of the gradient of relative disparity between abutted stereoscopic surface edges in the simultaneous condition. The effect of this relative disparity information between edges of targets depends on target separation in space (Gillam & Blackburn, 1998) and presumably in time. These two factors affected subjects differently.

Horizontal Version Errors

In the sequential with gaze shift condition in Experiment 2, subjects made a vertical gaze shift to image spatially separated reference and test stimuli onto the fovea where disparity resolution is higher than in the periphery. The discrimination thresholds (filled circles in Figure 4) were independent of vertical target separation (vertical saccade amplitude). The constant thresholds at all target separations indicate that horizontal version errors associated with vertical gaze shifts had little if any influence on slant threshold or that there was little horizontal version error with vertical saccades.

More horizontal version errors would be expected to accompany horizontal than vertical gaze shifts. Horizontal version errors could elevate stereo-slant thresholds by introducing errors in estimates of azimuth that are used to correct slant estimates in oculo-centric and head-centric coordinates (Backus et al., 1999). Horizontal version signals are most influential for estimates of target azimuth when vertical disparity information for azimuth is minimized with short-height stimuli, such as was used in our experiments.

The possible influence of horizontal version errors on azimuth estimates for recovering slant was examined in Experiment 3 by comparing sequential stereo-slant discrimination thresholds measured with saccades between vertically and horizontally separated test and reference stimuli, as a function of their separation. The thresholds for the two conditions were equal and independent of target separation (Figure 6) demonstrating either that both measures of sequential stereo-slant thresholds were unaffected by horizontal version errors or that version errors were independent of saccade amplitude. The latter possibility is unlikely given the prior reports of increased variability of eye position with saccade amplitude (Boucher et al., 2001).

Horizontal Vergence Errors

Experiment 4 provided indirect evidence for the presence of horizontal vergence errors that increased with vertical saccade amplitude. This experiment measured sequential stereo-dot depth discrimination thresholds as a function of vertical separation while allowing saccades between the sequentially presented reference and test targets. Horizontal vergence errors are believed to introduce independent disparity errors for absolute disparities subtended by sequentially presented test and reference dots as well as relative disparity errors computed from a presumed differencing process (Westheimer, 1979a). Results revealed that the sequential stereo-depth thresholds (open circles), measured with gaze shifts increased with target separation while the sequential stereo-slant thresholds (filled circles) measured with gaze shifts remained constant (Figure 7). This difference emphasizes the point that the horizontal vergence errors do appear to elevate the depth-discrimination threshold; however, they have little if any effect on slant discrimination.

Horizontal vergence errors associated with gaze shifts are assumed to be similar in stereo-slant and stereo-depth tasks, yet the effect of these oculomotor errors on the discrimination thresholds is greater for the stereo-depth task. Presumably this is because the disparity information was processed differently in each task. In stereo-depth task, thresholds are based on a sequential comparison of absolute disparities subtended by the test and reference targets. Each absolute disparity is presented sequentially such that they are contaminated by independent horizontal vergence errors for the two targets. In stereo-slant task, relative disparity is present in each slant stimulus and horizontal vergence errors could be cancelled in a presumed differencing process for computing relative disparity (Westheimer, 1979a).

Conclusions

Normally we can inspect the stereo-slant variations of an extended surface, such as the ground plane, either with fixed gaze or with gaze shifts. With fixed gaze, surface locations in different directions are viewed at the same time (simultaneous stereopsis) in foveal and peripheral locations. With saccadic gaze shifts, surface locations are viewed at different times (sequential stereopsis), both at the fovea. When inspecting widely separated surface locations, both strategies may be involved. Simultaneous comparisons could be made between foveal and peripheral views, followed by sequential foveal comparisons between saccadic gaze shifts.

Without gaze shifts, the most prominent factor that limits stereo-slant thresholds is reduced disparity resolution in the periphery. *With* gaze shifts, the main factors that limit sequential stereo-slant performance are memory loss and reduced use of the gradient of relative disparity between abutted stereoscopic edges. Even though horizontal vergence errors do occur with normal vertical and horizontal saccadic gaze shifts, they have little influence on sequential stereo-slant thresholds, but a large effect on sequential stereo-depth thresholds when targets are widely separated.

Depending on the target separation, both simultaneous and sequential viewing strategies have their own advantages and disadvantages. Our results indicate that the critical separation at which performance is improved by gaze shifts is approximately 4 deg.

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