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Effects of horizontal and vertical additive disparity noise on stereoscopic corrugation detection

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Abstract

Stereoscopic corrugation detection in the presence of horizontal- and vertical- additive disparity noise was examined using a signal detection paradigm. Random-dot stereograms either represented a 3-D square-wave surface with various amounts of Gaussian-distributed additive disparity noise or had the same disparity values randomly redistributed. Stereoscopic detection of 2 arcmin peak amplitude corrugations was found to tolerate significantly greater amplitudes of vertical-disparity noise than horizontal-disparity noise—irrespective of whether the corrugations were horizontally or vertically oriented. However, this directional difference in tolerance to disparity noise was found to reverse when the corrugation and noise amplitudes were increased (so as to produce equivalent signal-to-noise ratios). These results suggest that horizontal- and vertical-disparity noise pose different problems for dot-matching and post-matching surface reconstruction as corrugation and noise amplitudes increase.

Keywords: Stereopsis; Detection; Surface; Depth; Disparity; Noise

1. Introduction

Our ability to perceive three-dimensional structures from Julesz-type random-dot stereograms is remarkable (Julesz, 1960, 1964, 1971). Despite the lack of overt monocular cues to cyclopean shape in these stereograms, we have little difficulty: (1) matching corresponding dots from the two eyes' images; (2) accurately extracting their binocular disparities; (3) combining disparity samples from across the visual field to form disparity maps; and (4) using these disparity maps to calculate depth and surface shape. Of the above achievements, the correspondence problem (stage 1) is generally regarded as the most challenging—since each dot in the left eye's image could potentially be matched with numerous identical dots in the right eye's image. However, many situations also pose significant post-matching problems (stages 2, 3 and 4)—for example, calculating a 3-D surface shape should be quite difficult when the disparity map is not locally smooth.

Over the last 40 years, theorists have identified many rules and constraints, which could be used (often in conjunction) to solve the correspondence problem (for a review, see Howard & Rogers, 1995). One common component in computational models of binocular matching is the epipolar constraint—for any image point in one eye, the corresponding point must lie on the corresponding epipolar line of the other eye (assuming that the eyes are vertically and torsionally aligned). This constraint effectively reduces the search space for matching dots from two-dimensions (horizontal and vertical) down to one (along the epipolar line). Initial findings appeared consistent with the epipolar constraint—depth judgements and interocular correlation detection were dramatically impaired when the dots in small, static random-dot stereograms were given vertical disparities of 4–10 arcmin (Nielsen & Poggio, 1984; Prazdny, 1985; Harris & Parker, 1994b). However, recent studies have shown that binocular correspon-

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dence can tolerate substantial perturbations in the vertical locations of corresponding dots (Rogers & Bradshaw, 1996; Stevenson & Schor, 1997). For example, Stevenson and Schor (1997) found that observers could detect interocular correlation and make accurate near/far depth discriminations when corresponding dots in their 12° diameter, dynamic random-dot stereograms had vertical disparities of 45 arcmin or more.

Since binocular matching is not constrained to epipolar lines, this raises the following questions. (1) Does stereoscopic matching in the vertical dimension differ from that in the horizontal dimension? (2) What effects do these extracted vertical disparities have on the recovery of horizontal-disparity defined surface structure? One way to address the above questions would be to examine these stereoscopic processes in the presence of vertical additive disparity noise. While there have been no studies of the effects of vertical-disparity noise on dot matching and post-matching surface reconstruction, several studies have examined the effects of horizontal-disparity noise on these processes (Harris & Parker, 1992, 1994a,b; Lankheet & Lennie, 1996; Palmisano, Allison, & Howard, 2000). In an important study, Harris and Parker (1994a) presented human and ideal observers with random-dot stereograms representing a vertically oriented step edge in depth with various amounts of Gaussian-distributed additive horizontal-disparity noise. Both human and ideal observers had to indicate which side of the display appeared nearer to them in depth. Harris and Parker found that statistical efficiency[1] on this task fell from ~10% to ~0.1% as the standard deviation of the horizontal-disparity noise increased from 1 to 6 arcmin. In follow-up experiments, using (planar patch and line) stimuli that minimized or eliminated the correspondence problem, they found that post-matching efficiency remained roughly constant as the horizontal-disparity noise increased. By a process of deduction, they concluded that their original finding of a dramatic decline in efficiency with increasing horizontal-disparity noise was due to noise increasing the difficulty of matching dots in random-dot stereograms.

The current experiment expands on the research of Harris and Parker by comparing the effects of Gaussian-distributed *horizontal- and vertical- additive disparity noise* on the ability to detect a disparity-defined surface with square-wave modulations in depth. We are particularly interested in: (1) whether there are any differences in the tolerance to these two types of noise, and if so (2) at what stage/s of processing do these differences arise (dot matching or post-matching)? Since this task potentially requires greater post-matching processing than detection of a single step edge, it is possible that both types of noise could produce significant difficulties at the dot-matching and post-matching surface reconstruction stages of processing.

2. Experiment 1: corrugation detection with vertical-disparity noise

2.1. Method

2.1.1. Observers

Three observers (aged between 29 and 39 years) participated in this experiment. SAP (the first author), XF and HJ (naïve to the experimental hypotheses) had normal or corrected-to-normal vision with a stereoacuity of at least 20 s of arc (Randot stereovision test). All three observers had participated in many previous experiments on stereoscopic surface detection and were given several hundred practice trials before commencing the experiment.

2.1.2. Apparatus

Random-dot stereograms were generated on a Macintosh G3 Power PC and presented on a 17 inch Apple Vision monitor (with a 120 Hz refresh rate and a 1024 horizontal × 384 vertical pixel resolution) in a completely dark room. A StereoGraphics GDC-3 display splitter was used to present these stereoscopic displays to an observer wearing a pair of CrystalEyes stereo shutters. This alternated the presentation of the left and right eyes' views on the screen in synchrony with the shuttering of the glasses (transparent to opaque at 60 Hz), which ran at half the video card refresh rate (120 Hz). This method of stereoscopic presentation ensured that there were no differences in the alignment, linearity and luminance of the two images. However, it had two main disadvantages: (1) there was ~8% cross-talk between the left and right images (produced by transmission in the closed phase, phosphor persistence and lags in the rise and fall time of LCD shutters when viewing our dim displays); and (2) horizontal pixel resolution was twice as fine as vertical pixel resolution. While the cross-talk could be regarded as an additional source of interference to the detection task[2] (effecting all displays equally), the resolution difference posed a more serious

[1] Statistical efficency (F) was calculated by comparing experimental human detection (d'_e) with that of an ideal observer (d'_i), $\{F=(d'_e/d'_i)^2\}$. Unlike, human observers, the ideal observer performed the dot-matching task perfectly and hence recovered the ideal disparity map.

[2] Previous estimates of the cross-talk in these shutters have ranged from 5% (Livingstone, 1996) to 13% (Mallot, Roll, & Arndt, 1996). This cross-talk would be expected to interfere with the detection of square-wave corrugations (introducing a weak plane at zero disparity). Control experiments, which presented images dichoptically with a Wheatstone stereoscope to an additional naive observer (MH), have replicated the major findings in this paper.

problem when comparing the effects of horizontal- and vertical-disparity noise. The steps taken to remove this potential confound are described in the stimuli section below. A chin rest kept the observer's head square to the screen at a distance of 110 cm. Surrounding fixtures were covered by black card and black sheets to remove extraneous distance information.

2.1.3. Stimuli

Random-dot stereograms consisted of two half-images subtending an area of 9° H × 9° V. Each half-image consisted of 5184 blue dots on a dark background. The dot density was 9% or 64 dots/deg^2, and the average luminance was 0.25 cd/m^2 (when viewed through the shutters). 'Dots' subtended an area of 4 arcmin at the viewing distance of 110 cm. These antialiased stereo half-images, produced by oversampling and decimation, were asymmetrically sized in terms of the number of pixels to compensate for the rectangular shape of pixels during display splitting. To test whether this manipulation sufficiently compensated for horizontal–vertical differences in screen resolution, observers ran four sessions when the monitor was upright and four sessions when the monitor was rotated 90° from vertical. Random-dot stereograms were of two kinds.

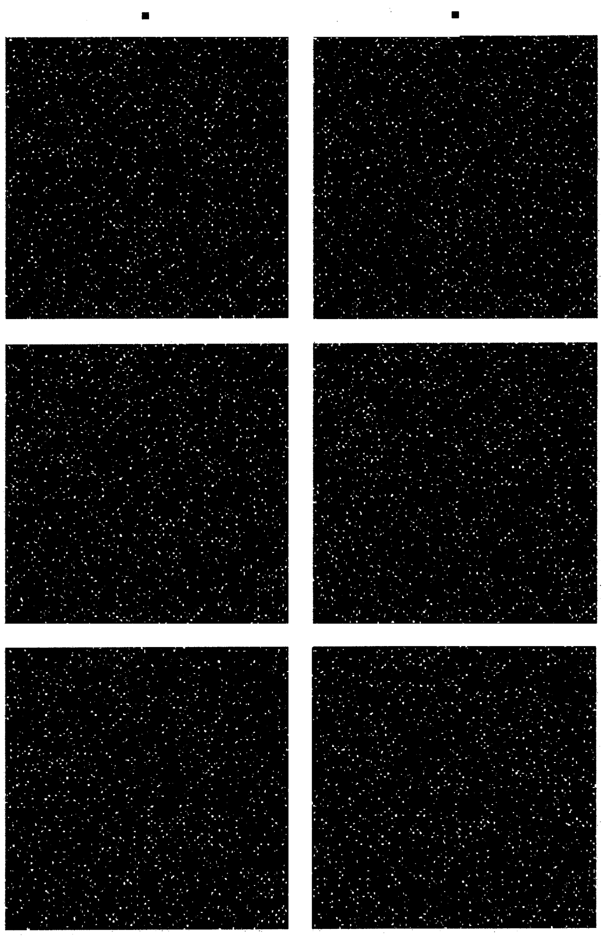

Fig. 1. Random-dot stereogram pairs representing the stimuli used in Experiment 1. When cross-fused, they portray horizontal square-wave gratings in depth either with or without additive disparity noise superimposed (top 'Pure signal'; middle 'Signal + horizontal disparity noise'; bottom 'Signal + vertical disparity noise').

1. 'Signal + noise' displays represented square-wave surfaces with horizontally oriented corrugations in depth (see Fig. 1 'Top'). The pattern of horizontal-disparities defining each surface was produced by shifting dots in opposite directions in the left and right stereo half-images (producing disparities of either +2 or −2 arcmin). [Note that for displays viewed when the monitor was rotated 90° from vertical, the pattern of horizontal disparities defining the surface was actually produced by shifting dots in opposite vertical directions (relative to the screen) in the two half images.] Various amounts of Gaussian distributed horizontal- or vertical-disparity noise were then added to these half-images (standard deviations of either 0, 2, 4, 6 or 8 arcmin—see Fig. 1 'Middle' and 'Bottom'). Three different signal spatial frequencies were examined—0.22 cpd (two troughs and two peaks), 0.44 cpd (four troughs and four peaks), or 0.88 cpd (eight troughs and eight peaks)—with surface phase varying randomly from trial to trial.
2. 'Noise' Displays were created by scrambling 'Signal + noise' stimuli along the vertical dimension. This destroyed surface representation while preserving the disparity distribution.

2.1.4. Procedure

Observers were informed that they would be viewing a series of 3-D displays, consisting of target stimuli depicting a 3-D square-wave surface (with two, four or eight troughs and peaks) and distracter stimuli appearing as a 3-D volume or two transparent planes. They were instructed that after they had resolved each display (by shifting their attention over the whole display), they were to indicate whether or not they saw a square-wave surface in depth. Following these instructions and the presentation of sample stimuli, observers commenced the experiment by pressing the space bar on the keyboard. As soon as they had resolved each display (viewed without an explicit or implicit fixation point), observers indicated whether or not the target signal was present by pressing one of two buttons ('yes' and 'no'). The stereogram was displayed until a response was recorded and then the monitor turned black for 2 s—this intertrial interval was designed to reduce after-images and disparity aftereffects. Observers ran eight experimental sessions—within each of these, equal numbers of 'Signal + Noise' and 'Noise' displays were presented in a random order.[3]

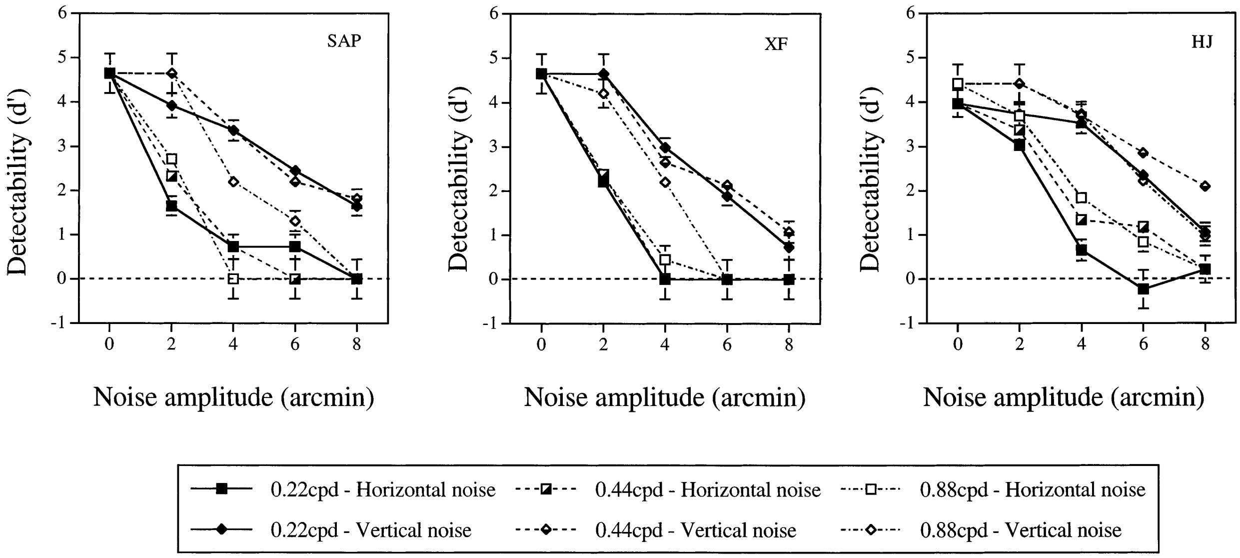

Fig. 2. Detectability of a horizontal square-wave grating in depth (d') as a function of both the spatial frequency of its depth modulation (0.22, 0.44 or 0.88 cpd) and the RMS amplitude of the added horizontal- or vertical-disparity noise (0–8 arcmin). Error bars show the standard errors of the mean (Experiment 1).

2.1.5. Analyses

Each observer's 'Yes' responses in the presence or absence of a stereoscopically defined square-wave surface in depth were converted into hit rates (H) and false alarm rates (F). These estimated probabilities (ranging between 0 and 1) were then converted into z-scores and used to calculate d prime (d')—the measure of sensitivity used in signal detection theory $\{d' = z(H) - z(F)\}$. The 95% confidence intervals for these d' values, CI(d'), were calculated as follows:

$$\mathrm{var}(d') = H(1-H)/N_{\mathrm{H}}[\phi(H)]^2 + F(1-F)/N_{\mathrm{F}}[\phi(F)]^2,$$

$$\mathrm{CI}(d') = 1.95 \times [\mathrm{var}(d')]^{1/2}$$

where N_{H} = number of hits, N_{F} = number of false alarms, $\phi(H) = 2\pi^{-1/2}\exp[-0.5z(H)^2]$, and $\phi(F) = 2\pi^{-1/2}\exp[-0.5z(F)^2]$ (MacMillan & Creelman, 1991).

2.2. Results and discussion

Stereoscopic detection of horizontally oriented, square-wave corrugations in depth was remarkably robust in the presence of substantial additive disparity noise. Of interest, corrugation detection was found to be more tolerant to vertical-disparity noise than to horizontal-disparity noise (see Fig. 2). Since this greater tolerance to vertical-disparity noise persisted when the horizontal-vertical asymmetry in display resolution was reversed (trends were very similar for both the upright and 90° rotated monitor orientations), we conclude that this effect was perceptual in nature and that antialiasing sufficiently compensated for display asymmetry. Overall, corrugation detection was found to be significantly more sensitive in the presence of 2–8 arcmin RMS amplitudes of vertical-disparity noise than in the presence of the same RMS amplitudes of horizontal-disparity noise [d' differences of 1.9 ± 0.6 (SAP), 1.1 ± 0.6 (XF), 1.8 ± 0.3 (HJ)]. While we found a greater tolerance to vertical-disparity noise for each of the spatial frequencies tested, the extent of this tolerance appeared to be less for 0.88 cpd corrugations (see Fig. 2). As the amount of horizontal-disparity noise that could be tolerated did not vary with corrugation spatial frequency[4], it appears that observers SAP and XF were more susceptible to vertical-disparity noise when displays depicted high spatial frequency corrugations.

Since there were several important differences between our experiments and those of Harris and Parker (1994a), we could not be sure that the effects of additive disparity noise were due solely to difficulties in dot matching. First, our random-dot stereograms had a lower dot density (64 dots/deg^2) than those used by Harris and Parker (94 dots/deg^2), which might have

[3] We used a 'yes–no' procedure, where the 'Signal + Noise' and reference 'Noise' stimuli were presented in a random order in our experiments {our method was similar to that used by Van Meerten and Barlow (1981) to examine the detection of sinusoidal modulations in random-dot images}. Recent research has shown that this procedure can yield very similar results to the alternative 2-interval-forced-choice procedure (thresholds tend to be slightly elevated with the 'yes–no' procedure—Gu & Green, 1994; Mills, Dubno, & He, 1996). Simply measuring the percentage correct is susceptible to shifts in either the observer's criterion or level of attention, so we also monitored their hit and false alarm rates. False alarm rates were typically quite low (rarely exceeding 0.05).

[4] Lankheet and Lennie (1996) have also reported that the amount of horizontal-disparity noise that could be tolerated in square-wave detection did not vary as a function of spatial frequency.

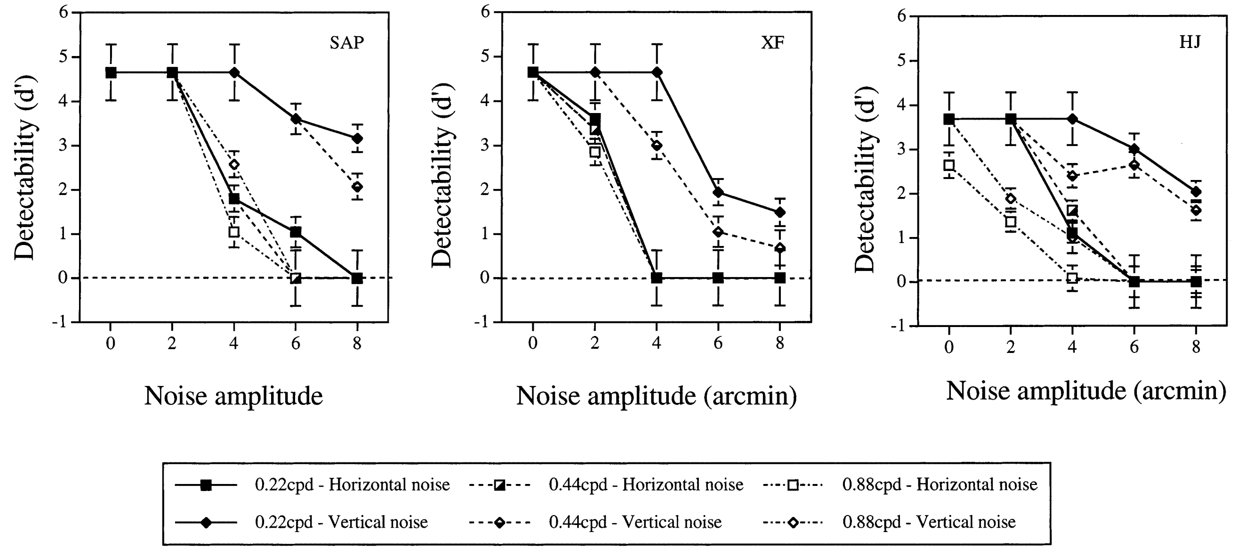

Fig. 3. Detectability of a vertical square-wave grating in depth (d') as a function of both the spatial frequency of its depth modulation (0.22, 0.44 or 0.88 cpd) and the RMS amplitude of the added horizontal- or vertical-disparity noise (0–8 arcmin). Error bars show the standard errors of the mean (Experiment 2).

reduced the complexity of the correspondence problem. A second difference was that Harris and Parker's task of detecting the sign of a disparity step potentially required less post-matching processing (it could be achieved with fewer dots) than the task of detecting a 3-D periodic surface. A third difference was that Harris and Parker examined the statistical efficiency of their task in the presence of horizontal-disparity noise (determined by comparing the detection performance of human and ideal observers) rather than human detection performance. A fall in efficiency is not necessarily the same as a fall in human detection performance (in fact, Harris and Parker endeavored to keep human detection performance constant as disparity noise increased, by varying the size of the disparity step). These density, task and measurement differences between the two experiments increase the likelihood that the differential tolerance to horizontal- and vertical-disparity noise arose during post-matching processing.

3. Experiment 2: effect of corrugation orientation

In Experiment 1, 'Signal + noise' displays always depicted horizontally oriented square-wave corrugations in depth. Experiment 2 examined whether the greater tolerance to vertical-disparity noise persists for vertically oriented square-wave corrugations. Previous research has shown that, in the absence of noise, vertically oriented sinusoidal corrugations have higher detection thresholds (Rogers & Graham, 1983; Bradshaw & Rogers, 1993, 1999) and less perceived depth (suprathreshold) than horizontally oriented sinusoidal corrugations. So it is possible that vertically oriented square-wave corrugations in depth will be more susceptible to both horizontal- and vertical-disparity noise compared to horizontally oriented square-wave corrugations. However, unlike random-dot stereograms representing horizontally oriented square-wave corrugations in depth, random-dot stereograms representing vertically oriented square-wave corrugations in depth are not fully cyclopean (monocularly visible density variations arise in the latter, but not the former—Tyler & Raibert, 1975). So it is also possible that monocular information about the presence/absence of the signal will render corrugation detection more robust to both horizontal- and vertical-disparity noise.

3.1. Method

The observers, apparatus, stimuli and procedure were identical to those of the previous experiment with the following exception. 'Signal + noise' displays always depicted a surface with vertical, rather than horizontal, square-wave corrugations in depth.

3.2. Results and discussion

Overall, detection of vertically oriented square-wave corrugations was found to be more immune to disparity noise than detection of horizontally oriented square-wave corrugations (examined in Experiment 1). This improvement could have been due either to the observers' increased familiarity with the task and stimuli or to monocularly available density information about the presence/absence of the signal. Importantly, corrugation detection performance was still more immune to vertical-disparity noise than to horizontal-disparity noise (see

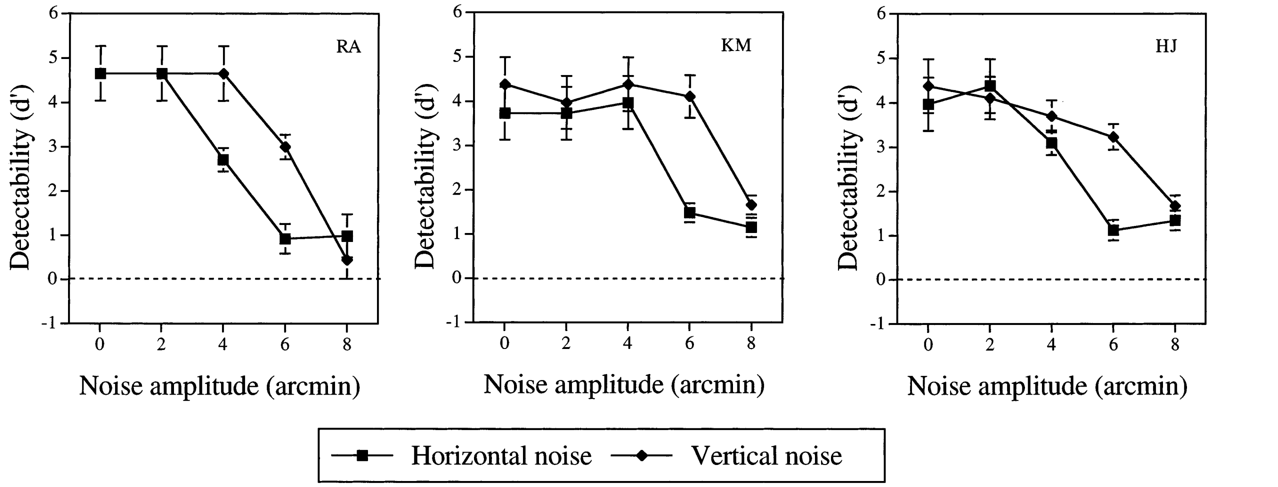

Fig. 4. Detectability of a horizontal square-wave grating in depth (d') as a function of the RMS amplitude of the added horizontal- or vertical-disparity noise (0–8 arcmin)—when the absolute ranges of horizontal and vertical disparity were equated. Error bars show the standard errors of the mean (Experiment 3).

Fig. 2). Overall, corrugation detection was significantly better in the presence of 4–8 arcmin RMS amplitudes of vertical-disparity noise than in the presence of the same RMS amplitudes of horizontal-disparity noise [d' differences of 1.6 ± 0.5 (SAP), 1.7 ± 0.6 (XF), 1.2 ± 0.3 (HJ)]. As in Experiment 1, while observers demonstrated a greater tolerance to vertical-disparity noise for each of the spatial frequencies tested, the extent of this tolerance appeared to be less for 0.88 cpd corrugations (see Fig. 3).

Since tolerance to disparity noise did not depend on the interaction between the direction of the disparity noise and the orientation of the corrugations, this finding would appear to reflect a true anisotropy. As a result, the following experiments all examine the effects of horizontal- and vertical-disparity noise on horizontally oriented square-wave corrugations in depth.

4. Experiment 3: comparing equivalent ranges of horizontal and vertical disparity

One possible explanation for the greater immunity to vertical-disparity noise demonstrated in Experiments 1 and 2 is based on the fact that the range of vertical disparity in displays with vertical-disparity noise was less that the range of horizontal disparity in displays with horizontal-disparity noise (when the RMS amplitude of the noise was equated). In displays with vertical-disparity noise, the vertical disparity of each dot pair was due solely to noise, whereas in displays with horizontal-disparity noise, the horizontal disparity of each dot pair was due to a combination of signal amplitude and noise. So, if the search area for matching dots is roughly symmetrical across the horizontal and vertical dimensions,[5] a dot pair's disparity would have been more likely to exceed the upper limit in a horizontal-noise display than in a vertical-noise display. To test this possibility, we examined the effect that the two different types of disparity noise had on the detection of displays containing square-wave modulations of both horizontal and vertical disparity. While the horizontal disparity signal was consistent with a 3-D surface, the vertical disparity signal was expected to have little effect on surface perception. Since these two disparity modulations had the same amplitude, the overall range of vertical disparity (vertical-disparity signal and noise) was equivalent to the overall range of horizontal disparity (horizontal-disparity signal and noise).

4.1. Method

4.1.1. Observers

Two new observers participated in this experiment (29—33 years of age). RA was one of the experimenters (he replaced SAP) and observer XF was replaced by a naïve observer KM. Both met the observer requirements mentioned previously.

4.1.2. Stimuli

Displays were identical to those of Experiment 1 with the following exceptions. 'Signal' displays contained square-wave modulations of both horizontal and verti-

[5] Neurophysiological and psychophysical support exists for this notion. Binocular neurons appear to respond in a roughly isotropic manner to positional disparities (Nikara et al., 1968; Ferster, 1981; LeVay & Voigt, 1988; Anzai et al., 1997). Similarly, Stevenson and Schor (1997) have found that interocular correlation detection in the horizontal dimension is similar to that in the vertical dimension.

cal disparity—these had the same peak amplitude (2_ arcmin), orientation (vertical modulations of disparity produced horizontally oriented corrugations) and spatial frequency (0.44 cpd). 'Signal + noise' displays were then created by adding horizontal- or vertical-disparity noise to these signals. As in Experiments 1 and 2, 'Noise' displays were created by scrambling the 'Signal + noise' displays along the vertical dimension.

4.2. Results and discussion

The greater immunity to vertical-disparity noise persisted when the overall ranges of horizontal- and vertical-disparity noise were equated in this experiment (see Fig. 4). For observer RA, corrugation detection was significantly more sensitive in the presence of 4 arcmin RMS amplitudes of vertical-disparity noise compared to 4 arcmin RMS amplitudes of horizontal-disparity noise—this trend did not reach significance for the other two observers [d' differences of 1.9 ± 1.3 (RA), 0.4 ± 1.6 (KM) and 0.5 ± 0.6 (HJ)]. For all three observers, corrugation detection was significantly more sensitive in the presence of 6 arcmin RMS amplitudes of vertical-disparity noise compared to 6 arcmin RMS amplitudes of horizontal-disparity noise [d' differences of 2.1 ± 0.8 (RA), 2.6 ± 1.0 (KM) and 2.1 ± 0.7 (HJ)]. There was, however, no difference in sensitivity in the presence of horizontal and vertical disparity at the maximum noise amplitude [d' prime differences of -0.17 ± 1.2 (RA), 0.5 ± 0.6 (KM) and 0.3 ± 0.6 (HJ)].

The greater tolerance to vertical-disparity noise persisted in this experiment. Performance never reached chance for any of the observers—even when the signal was degraded by horizontal-disparity noise with an RMS amplitude of 8 arcmin. Perhaps the two new observers (RA and KM) were more sensitive to the depth modulations than those they replaced (SAP and XF). Similarly, the improved performance of the experienced observer (HJ) might reflect the extensive practice she had on this task in Experiments 1 and 2. However, it is also possible that this overall increase in tolerance to disparity noise was due to the additional vertical-disparity signal in these 'Signal + noise' displays. While the square-wave corrugations of vertical disparity would be expected to have little effect on surface perception, they might have aided in distinguishing the 'Signal + noise' displays from 'Noise' displays. In particular, the vertical disparities defining the horizontally oriented corrugation could have provided monocularly available density information about the presence/absence of the signal (in the same fashion that horizontal disparities defining a vertically oriented corrugation produced non-cyclopean displays in Experiment 2).

5. Experiment 4: effect of corrugation and noise amplitude

In principle, the greater tolerance to vertical-disparity noise found in Experiments 1–3 could have arisen at any stage of stereoscopic processing. One possibility was that vertical-disparity noise posed fewer problems for dot matching. For example, since horizontal disparities tend to be larger than vertical disparities in natural scenes, it is possible that the dot matching occurred over a smaller range in the vertical dimension compared to the horizontal dimension. If the matching area was asymmetrical, then dot pairs with large horizontal perturbations would have been matched (and subsequently treated as depth noise), while dot pairs with large vertical perturbations would have been treated as being unpaired. Since research has shown that binocular correspondence is remarkably robust in the presence of large numbers of unpaired dots (e.g. Julesz, 1960; Cormack, Landers, & Ramakrishnan, 1997), increasing the amplitude of vertical-disparity noise might be expected to have little effect on stereoscopic surface detection.

Alternatively, the greater tolerance to vertical-disparity noise could have been due to the fact that it posed fewer problems for post-matching processing. While adding horizontal-disparity noise (depth noise) to the horizontal disparity-defined square-wave signal would have produced a very jagged surface, adding vertical-disparity noise would not have affected the horizontal disparities extracted from *correctly* matched points (these would still have been consistent with a pure square-wave surface).[6] Further, since vertical disparities are averaged over a wider area than horizontal disparities for slant perception and distance scaling (Stenton, Frisby, & Mayhew, 1984; Adams et al., 1996; Kaneko & Howard, 1996, 1997; Howard & Pierce, 1998; Pierce, Howard, & Feresin, 1998; Porrill, Frisby, Adams, & Buckley, 1999), the visual system might have reduced the vertical disparity estimate at any local area of the display towards zero (the mean of the Gaussian noise distribution), and the similarity of these estimates might in turn have facilitated the combination of disparity samples across the visual field.

Experiment 4 was designed to distinguish between matching and post-matching explanations of our noise tolerance findings. Specifically, it examined whether the greater tolerance to vertical-disparity noise persists when corrugation and noise amplitudes are increased. If the greater tolerance to vertical-disparity noise arose

[6] Spurious dot matches due to vertical-disparity noise could have produced depth noise. However, since dot-matching difficulties appeared minor at modest corrugation and noise amplitudes, this indirect depth noise should have had a lesser effect on surface perception (compared to the direct depth noise produced by horizontal-disparity noise).

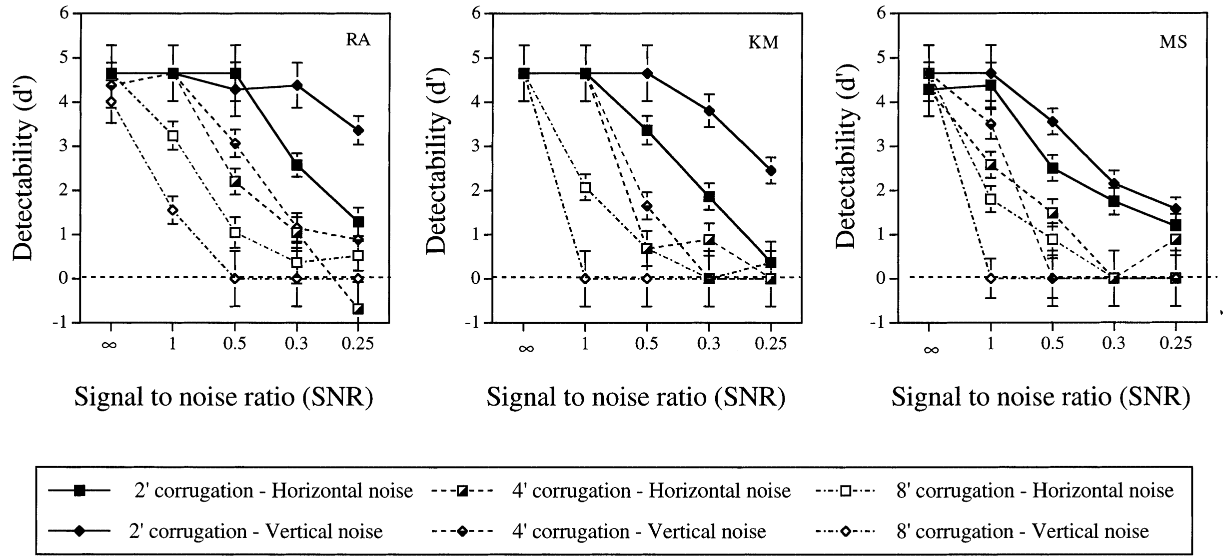

Fig. 5. Detectability of a horizontal square-wave grating in depth (d') as a function of its signal-to-noise ratio (SNR) [ratio of the depth modulation (2–8 arcmin) to the RMS amplitude of the horizontal- or vertical-disparity noise (0–8, 0–16, 0–24)]. Error bars show the standard errors of the mean (Experiment 4).

because dot-matching occurred over a smaller range in the vertical dimension, then the difference in noise tolerance would be expected to decline as corrugation and noise amplitudes increase—since dots with large horizontal disparities and substantial horizontal-disparity noise would be more likely to exceed the horizontal range of dot-matching and thus be treated as decorrelation noise rather than as depth noise. Alternatively, if this difference in tolerance arose because vertical-dis parity noise posed fewer problems for post-matching processing, then this trend would be expected to persist as corrugation and noise amplitudes increase—since vertical-disparity noise would only effect the signal indirectly, and vertical-disparity noise estimates would still be lower than horizontal-disparity noise estimates due to pooling.

5.1. Observers

Observer HJ was replaced by a naïve observer MS (46 years of age), who met the observer requirements mentioned previously.

5.2. Stimuli

Displays were identical to those of Experiment 1 with the following exception. Unlike the previous experiments, where the peak amplitude of the corrugation was always 2 arcmin, this experiment examined detection performance for three different corrugation amplitudes (2, 4 and 8 arcmin). We kept the signal-to-noise ratios (SNRs) equivalent across these corrugation amplitude conditions by adjusting the range of noise amplitudes for each (0–8 arcmin, 0–16 arcmin and 0–32 arcmin). A SNR of ∞ indicates a pure signal, a SNR of 1 indicates that the corrugation amplitude was equal to the RMS amplitude of the disparity noise, and SNRs of less than 1 indicate that the RMS amplitude of the noise exceeded the corrugation amplitude.

5.3. Results and discussion

Consistent with the findings of Experiments 1–3, all three observers were significantly more sensitive to the 2 arcmin amplitude corrugations in the presence of vertical-disparity noise (see Fig. 5). Observers RA and KM were more sensitive to vertical-disparity noise when SNRs were 0.3–0.25 and 0.5–0.25, respectively (d' differences of 1.4 ± 0.7 and 1.2 ± 0.7). The remaining observer (MS) was more sensitive to vertical-disparity noise when the SNR was 0.5 (d' difference of 1.1 ± 0.9). However, with 4 arcmin corrugation amplitudes, only observer RA's tolerance to vertical-disparity noise was significantly greater (for RA, the d' difference for SNRs of 0.5-0.25 was 0.8 ± 0.6; for KM, the d' difference for a SNR of 0.5 was 0.9 ± 1.0; for MS, the d' difference for a SNR of 1 was 0.9 ± 0.9). Interestingly, the direction of the difference in tolerance to disparity noise reversed with 8 arcmin amplitude corrugations. All three observers were significantly more tolerant to horizontal-disparity noise than to vertical-disparity noise with SNRs of 1 [d' differences of 1.7 ± 0.9 (RA), 2.1 ± 1.4 (KM) and 1.8 ± 1.1 (MS)]. However, there was no significant difference between the tolerance to horizontal- and vertical-disparity noise when this corrugation amplitude was tested at lower SNRs (0.5–0.25) [d' differences of 0.7 ± 0.9 (RA), 0.4 ± 1.0 (KM) and 0.5 ± 1.0 (MS)].

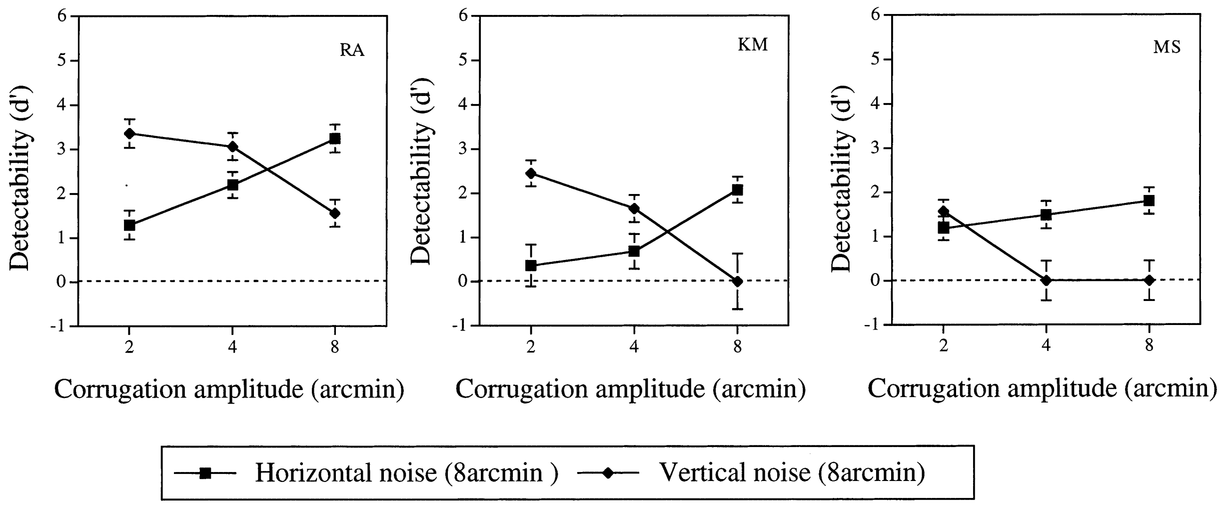

Fig. 6. Detectability of a horizontal square-wave grating in depth (d') in the presence of horizontal- and vertical-disparity noise (8 arcmin RMS amplitude) as a function of the amplitude of the depth modulation (2–8 arcmin) (Experiment 4).

These findings cannot be explained in terms of either dot-matching or post-matching surface reconstruction alone. Clearly, the post-matching hypothesis, which predicted that the greater tolerance to vertical-disparity noise would persist as corrugation and noise amplitudes increased, was not supported. Similarly, the asymmetrical matching area hypothesis—that tolerance to vertical-disparity noise would approach tolerance to horizontal-disparity noise as corrugation and noise amplitudes increased—did not predict that there would be a greater tolerance to horizontal-disparity noise at the largest corrugation amplitude.

In terms of absolute disparity noise (rather than SNR), tolerance to horizontal-disparity noise improved as the corrugation amplitude increased from 2 to 8 arcmin, whereas tolerance to vertical-disparity noise declined. This can be seen best by examining the effects of 8 arcmin RMS amplitudes of disparity noise since this absolute level of noise was tested on all three of the corrugation amplitudes. For example, observer RA's detection performance with 8 arcmin RMS amplitudes of horizontal-disparity noise improved from a d' of 1.3 to 3.2 as the corrugation amplitude increased from 2 to 8 arcmin. Conversely, his detection performance with the same amplitude of vertical-disparity noise declined steadily as the corrugation amplitude increased (from a d' of 3.4 for the 2 arcmin corrugation, to a d' of 3.1 for the 4 arcmin corrugation, and finally to a d' of 1.5 for the 8 arcmin corrugation). The two other observers showed similar trends (see Fig. 6).

Taken together, these results suggest that horizontal- and vertical-disparity noise pose different problems for dot-matching and post-matching surface reconstruction as corrugation and noise amplitudes increase. For the smallest corrugation condition, adding horizontal-disparity noise that exceeded the corrugation amplitude should have caused significant difficulties for post-matching surface reconstruction, while equivalent levels of vertical-disparity noise should have had little effect on surface reconstruction using correctly matched dots[6]. While surface reconstruction would have become easier when the same amount of horizontal-disparity noise was added to larger amplitude corrugations (since these 'Signal + noise' displays had larger SNRs), the effect of vertical-disparity noise on surface reconstruction should have remained the same irrespective of the corrugation amplitude. Thus, it seems likely that that the above findings were due in part to vertical-disparity noise increasing dot-matching difficulties as the corrugation amplitude increased. Stevenson and Schor (1997) have shown that the tolerance of both interocular correlation detection and depth judgment tasks to vertical-disparity decreases as the horizontal-disparity defining the depth difference increases. So, it seems likely that the larger horizontal-disparities defining 4 and 8 arcmin amplitude corrugations made it progressively more difficult to match the vertically disparate dots (compared to 2 arcmin amplitude corrugations).

6. General discussion

Since most binocular neurons tend to respond in a roughly isotropic manner to horizontal- and vertical-positional disparities (Ferster, 1981; LeVay & Voigt, 1988; Nikara, Bishop, & Pettigrew, 1968; Anzai, Ohzawa, & Freeman, 1997), one might expect that stereoscopic surface detection would be equally susceptible to horizontal- and vertical-additive disparity noise. However, the current experiments have shown that the visual system can respond quite differently to these two types of noise. Experiments 1–4 found that stereoscopic corrugation detection had a greater tolerance for vertical-disparity noise when noise and corrugation amplitudes were modest. However, in Experiment 4, the direction of this difference in tolerance was found to reverse when these noise and corrugation amplitudes increased (detection was more tolerant to horizontal-disparity noise than to vertical-disparity noise). We argue that these findings cannot be explained in terms of either dot-matching or post-matching surface reconstruction alone. Rather, we propose that horizontal- and vertical-disparity noise produce different problems for dot-matching and post-matching surface reconstruction as the range of horizontal and vertical disparities in the display increased. According to this proposal, the greater tolerance to vertical-disparity noise at modest corrugation and noise amplitudes arose because horizontal-disparity noise led to additional post-matching difficulties. (While observers should have been able to match most of the dots correctly with modest amplitudes of horizontal- and vertical-disparity noise, the horizontal disparity map produced by the former should have represented a much more jagged surface than that produced by the latter[6]). Conversely, the decreased tolerance to both horizontal- and vertical-disparity noise as corrugation and noise amplitudes increased was attributed to the observer's increasing difficulty matching dots. Finally, the greater tolerance to horizontal-disparity noise at large corrugation amplitudes was attributed to large horizontal disparities in the display limiting the maximum vertical disparity that could be matched (although this effect could also have been produced by the visual system having a smaller dot matching range in the vertical dimension).

How do our current findings compare with the previously reported effects of horizontal-disparity noise on the detection of a step edge in depth? While Harris and Parker (1994a) attributed dramatic decrements in efficiency to horizontal-disparity noise exacerbating dot-matching difficulties, they also identified an additional (more modest) decrement in efficiency, which they attributed to post-matching difficulties. The steps in disparity their observers had to detect (which ranged between 0.7 and 2.1 arcmin) were typically smaller than the amplitude of our disparity modulation, but the RMS amplitude of the noise was similar (1–6 arcmin). However, the stimuli and the task used in our experiments may have rendered post-matching difficulties more important, since: (1) our random-dot stereograms had a lower dot density than those used by Harris and Parker, which might have reduced the complexity of the correspondence problem; and (2) our corrugation detection task potentially required more post-matching processing than Harris and Parker's step edge detection task. Thus, it seems likely that the greater tolerance to vertical-disparity noise at modest amplitudes of signal and noise was due to horizontal-disparity noise producing an additional decrement in detection performance due to difficulties during post-matching surface reconstruction.

In the current experiments, horizontal-disparity noise always engaged the same horizontal-disparity system responsible for detecting the signal. We are currently investigating the effects of horizontal- and vertical-disparity noise on the detection of surfaces with vertical-disparity defined slant about the vertical axis (the induced effect—Ogle, 1938). Since previous research has found that the induced effect is absent or severely reduced when displays are less than 10 degrees in diameter (e.g. Westheimer, 1978; Kaneko & Howard, 1996), these stereoscopic displays are substantially larger than those used in the current study (60 degrees in diameter). The above theory predicts that vertical-disparity noise should have a greater effect on post-matching surface reconstruction in this situation. However, we do not expect that the relative tolerances to horizontal- and vertical-disparity noise will simply reverse. While only horizontal-disparity noise should result in substantial depth noise with horizontal-disparity defined signals, both horizontal- and vertical-disparity noise could potentially interfere with the post-matching surface reconstruction of vertical-disparity defined signals. One further complication is that unlike the square-wave signals examined in the current study, which were defined by step changes of relative horizontal-disparity, slant about the vertical axis is defined by gradients of absolute vertical disparity (Gillam, Flagg, & Finlay, 1984; Gillam, Chambers, & Russo, 1988). It is possible that the effects of vertical-disparity noise on the detection of a gradient of absolute vertical disparities will differ quite markedly from the effects of horizontal-disparity noise on the detection of a step change of relative horizontal disparities. This possibility will be tested by comparing the former with the effects of horizontal-disparity noise on the horizontal-disparity defined slant about the vertical axis (i.e. the geometric effect).

In conclusion, the current study supports a growing body evidence that stereopsis involves a complex 2-D, as opposed to a 1-D, search (e.g. Stevenson & Schor, 1997; Farell, 1998). However, the stereoscopic detection of corrugated surfaces also appears to involve substantial post-matching processing. We conclude that at large corrugation and noise amplitudes, horizontal- and vertical-disparity noise impair binocular correspondence to similar extents. However, at more modest corrugation and noise amplitudes, horizontal-, but not vertical-, disparity noise can significantly impair post-matching surface reconstruction.

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References

Adams, W., Frisby, J. P., Buckley, D., Gårding, J., Hippsley-Cox, S. D., & Porill, J. (1996). Pooling of vertical disparities by the human visual system. *Perception*, *25*, 165–176.

Anzai, A., Ohzawa, I., & Freeman, R. D. (1997). Neural mechanisms underlying binocular fusion and stereopsis: position vs. phase. *Proceedings of the National Academy of Sciences of the United States of America*, *94*, 5438–5443.

Bradshaw, M. F., & Rogers, B. J. (1993). Sensitivity to horizontally and vertically oriented stereoscopic corrugations as a function of corrugation frequency. *Perception*, *22*, 177.

Bradshaw, M. F., & Rogers, B. J. (1999). Sensitivity to horizontal and vertical corrugations defined by binocular disparity. *Vision Research*, *39*, 3049–3056.

Cormack, L. K., Landers, D. D., & Ramakrishnan, S. (1997). Element density and the efficiency of binocular matching. *Journal of the Optical Society of America A*, *14*, 723–730.

Farell, B. (1998). Two-dimensional matches from one-dimensional stimulus components in human stereopsis. *Nature*, *395*, 689–693.

Ferster, D. (1981). A comparison of binocular depth mechanisms in area 17 and 18 of the cat visual cortex. *Journal of Physiology (London)*, *311*, 623–655.

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

Gillam, B., Flagg, T., & Finlay, D. (1984). Evidence for disparity change as the primary stimulus for stereoscopic processing. *Perception & Psychophysics*, *36*, 559–564.

Gu, X., & Green, D. M. (1994). Further studies of a maximum-likelihood yes–no procedure. *Journal of the Acoustical Society of America*, *96*, 93–101.

Harris, J. M., & Parker, A. J. (1992). Efficiency of stereopsis in random-dot stereograms. *Journal of the Optical Society of America A*, *9*, 14–24.

Harris, J. M., & Parker, A. J. (1994a). Constraints on human stereo dot matching. *Vision Research*, *34*, 2761–2772.

Harris, J. M., & Parker, A. J. (1994b). Objective evaluation of human and computational stereoscopic visual systems. *Vision Research*, *34*, 2773–2785.

Howard, I. P., & Pierce, B. J. (1998). Types of shear disparity and the perception of surface inclination. *Perception*, *27*, 129–145.

Howard, I. P., & Rogers, B. J. (1995). *Binocular vision and stereopsis*. New York: Oxford University Press.

Julesz, B. (1960). Binocular depth perception of computer generated patterns. *Bell System Technical Journal*, *39*, 1125–1162.

Julesz, B. (1964). Binocular perception without familiarity cues. *Science*, *145*, 356–362.

Julesz, B. (1971). *Foundations of cyclopean perception*. Chicago, IL: University of Chicago Press.

Kaneko, H., & Howard, I. P. (1996). Relative size disparities and the perception of surface slant. *Vision Research*, *36*, 1919–1930.

Kaneko, H., & Howard, I. P. (1997). Spatial properties of shear disparity processing. *Vision Research*, *37*, 315–323.

Lankheet, M. J. M., & Lennie, P. (1996). Spatio-temporal requirements for binocular correlation in stereopsis. *Vision Research*, *36*, 527–538.

LeVay, S., & Voigt, T. (1988). Ocular dominance and disparity coding in cat visual cortex. *Visual Neuroscience*, *1*, 395–414.

Livingstone, M. S. (1996). Differences between stereopsis, interocular correlation and binocularity. *Vision Research*, *36*, 1127–1140.

MacMillan, N. A., & Creelman, C. D. (1991). *Detection theory: a user's guide*. New York: Cambridge University Press.

Mallot, H. A., Roll, A., & Arndt, P. A. (1996). Disparity-evoked vergence is driven by interocular correlation. *Vision Research*, *36*, 2925–2937.

Mills, J. H., Dubno, J. R., & He, N. (1996). Masking by ipsilateral and contralateral maskers. *Journal of the Acoustical Society of America*, *100*, 3336–3344.

Nielsen, K. R. K., & Poggio, T. (1984). Vertical image registration in stereopsis. *Vision Research*, *24*, 1133–1140.

Nikara, T., Bishop, P. O., & Pettigrew, J. D. (1968). Analysis of retinal correspondence by studying receptive fields of binocular single units in cat striate cortex. *Experimental Brain Research*, *5*, 353–372.

Ogle, K. N. (1938). Induced size effect. 1. A new phenomenon of binocular space perception. *AMA Archives of Ophthalmology*, *20*, 604–623.

Palmisano, S., Allison, R. S., & Howard, I. P. (2000). Effect of disparity noise on stereoscopic surface perception in human and ideal observers. *Proceedings of Intelligent Systems and Applications*, *1*, 1006–1012.

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.

Porrill, J., Frisby, J. P., Adams, W. J., & Buckley, D. (1999). Robust and optimal use of information in stereo vision. *Nature*, *397*, 63–66.

Prazdny, K. (1985). Vertical disparity tolerance in random-dot stereograms. *Bulletin of the Psychonomic Society*, *23*, 413–414.

Rogers, B. J., & Bradshaw, M. F. (1996). Does the visual system use the epipolar constraint for matching binocular images? *Investigative Opthalmology & Visual Science*, *37*, 684.

Rogers, B. J., & Graham, M. E. (1983). Anisotropies in the perception of three-dimensional surfaces. *Science*, *221*, 1409–1411.

Stenton, S. P., Frisby, J. P., & Mayhew, J. E. (1984). Vertical disparity pooling and the induced effect. *Nature*, *309*, 622–623.

Stevenson, S. B., & Schor, C. M. (1997). Human stereo matching is not restricted to epipolar lines. *Vision Research*, *37*, 2717–2723.

Tyler, C. W., & Raibert, M. (1975). Generation of random-dot stereogratings. *Behavior Research Methods and Instrumentation*, *7*, 37–41.

Van Meerten, A., & Barlow, H. B. (1981). The statistical efficiency for detecting sinusoidal modulation of average dot density in random figures. *Vision Research*, *21*, 765–777.

Westheimer, G. (1978). Vertical disparity detection: is there an induced size effect? *Investigative Ophthalmology*, *17*, 545–551.