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Depth interpolation with sparse disparity cues

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Abstract. The interpolation of stereoscopic depth given only sparse disparity information was investigated. The basic stimulus was a rectangle with zero disparity at one edge, and 20 or 30 min visual angle disparity at the other. The depth assigned to the ambiguous intervening locations was measured by means of a small briefly-flashed binocular comparison spot. For a stimulus consisting of a uniform rectangle presented on a background of random dots with zero disparity, interpolated depth was greater for a high mean contrast between rectangle and background than for a low mean contrast. Relative to a linear interpolation between the edges, a larger difference in edge disparity resulted in poorer depth interpolation. Depth interpolation based on rivalrous information was examined by filling the stimulus rectangle with narrow-band filtered noise which was uncorrelated between the two eyes. Four different passbands which were matched in apparent contrast were investigated. The results demonstrate that the rivalrous low-spatial-frequency content was resistant to interpolation; rivalrous high spatial frequencies did not interfere with depth interpolation. High-spatial-frequency stimuli yielded a percept similar to the uniform-field condition, whereas low-spatial-frequency stimuli lay in a depth plane near or even behind the background. In the latter case a transparent plane was perceived which was linearly interpolated between the two edges, and which floated above the rivalrous noise.

1 Introduction

When uniform rectangles of slightly different widths are presented to each of the two eyes, the subject usually perceives a rectangle tilted in depth (Ogle 1950; Blakemore 1970; Wilson 1976; Tyler and Sutter 1979; Halpern et al 1987). This observation is interesting because the only cue to depth is the disparity of the edges. Areas in the center of the rectangle are perceived as having intermediate depth values, although no point-by-point matching is possible. It is this process of inferring intermediate depth values between sparse disparate elements that we term 'depth interpolation'. The depth values assigned to these intermediate locations we call 'interpolated depth' since the observers are asked to judge the depth of these locations relative to a comparison stimulus with a well-defined disparity value. By using the term interpolated depth, we do not mean to imply a particular mechanism used to infer these depth values (such as spline interpolation, etc), but simply that a depth has been assigned to locations where disparity is ambiguous, and that this perceived depth is based, in part, on the depth values at locations where disparity is well-defined. In this paper, the term 'depth' is always used as a psychological magnitude, and 'disparity' as a stimulus variable.

Consider the stereogram illustrated in figure 1. In this stereogram only the edges carry disparity information. The disparities of the six edges in the stimulus are, from left to right, 0, 2, 4, 4, 2, and 0 min visual angle (from a viewing distance of 50 cm). These well-defined disparity values are illustrated as filled squares in figures 2a and 2b. We have shown this stereogram to a large number of observers, and two percepts predominate. Some subjects perceive the grey stripes as flat (as indicated by the solid lines in figure 2a). This percept would be expected if the stereogram is interpreted as three uniform rectangles lying on top of each other, with the smallest (light grey) rectangle occluding the medium-sized (mid-grey) one, which in turn occludes the largest

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(dark grey) one. We term this interpretation the 'occlusion explanation'. Other subjects perceive the uniform stripes as tilted, where the amount of slant is determined by the disparity of the edges (figure 2b), resulting in the percept of a truncated triangular prism. It is as if the perceived depth of the undetermined areas (the uniform grey stripes) was interpolated linearly between the edges.

A number of other researchers have touched on the issue of depth interpolation. The most relevant study was carried out by Collett (1985), who investigated extrapolation and interpolation of surfaces in depth with stimuli containing both binocular and monocular regions. The main conclusion was that subjects can extrapolate depth across edges, although there is large variability between subjects and even for a single subject when tested on different occasions. Similar to the demonstration described above, Collett found that subjects sometimes perceived a monocular region between two binocular regions with different disparity values as slanted, and sometimes they reported two front-parallel planes without a slant in this monocular region. Bülthoff and Mallot (1987) have reported similar observations of the resolution of depth in ambiguous image regions. They superimposed a black annulus on a larger grey disc. The annulus had crossed disparity, and the disc had zero disparity. As in the previous example, the depth between the edges of the disc and the annulus was interpolated. The resulting percept was a truncated cone coming forward to the observer, rather than simply a black annulus in front of and occluding a grey disc. Using a simple random-dot stereogram, Julesz (1971, figure 4.5-5) demonstrated that sparse disparity information

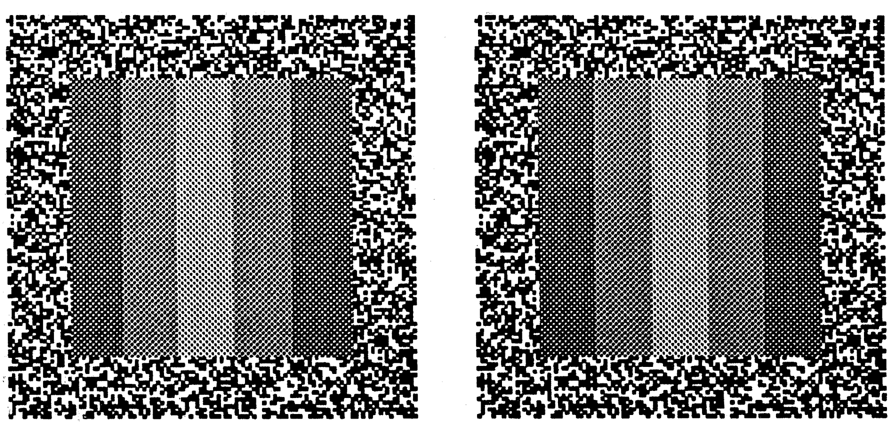

Figure 1. A stereogram providing disparity information only at edges. The disparities of the edges, from left to right, are 0, 2, 4, 4, 2, and 0 min visual angle when viewed from a distance of 50 cm. A binocular protruding comparison frame is embedded in the random-dot background.

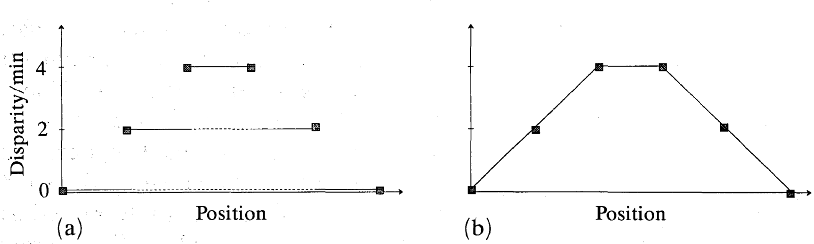

Figure 2. Possible percepts of figure 1. The well-defined disparities are indicated by filled squares. (a) One possible percept interprets the stereogram in figure 1 as consisting of three rectangles of different sizes lying on top of each other. (b) Another percept assigns a depth to ambiguous locations by linearly interpolating between the disparities of the surrounding edges.

(5%) was sufficient to perceive the stereogram in depth as a uniformly textured plane rather than as single isolated dots. Gulick and Lawson (1976) have demonstrated that the outline of a figure suffices to determine the perceived depth of the whole figure. Computational models for depth interpolation have been proposed by Grimson (1981, 1983) and Terzopoulos (1983).

All these empirical studies demonstrate cases in which a spatial location which has ambiguous correspondence between the retinal images of the two eyes takes on a depth value similar to the depth values of the neighboring points. In this paper we are interested in the conditions under which depth interpolation occurs. We investigate whether changes in stimulus-background contrast, the disparity difference between the edges, or the spatial-frequency content affect depth interpolation. Furthermore, the effect of rivalrous versus nonrivalrous depth information on interpolation is addressed. Models for binocular vision (see Marr 1981 for a review) or, more specifically, models of depth interpolation (Grimson 1981) will need to take these factors into account.

To investigate the phenomenon of depth interpolation, we concentrate on the much simpler stimulus of a single rectangle with different disparities at the two edges (see figure 3a), surrounded by a background with zero disparity. With such a stimulus the occlusion explanation is not possible, and percepts of a tilted plane are seen by almost all subjects.

In this paper we concentrate on the measurement of interpolated depth, and the effect that certain stimulus manipulations have on the perceived interpolated surface, in order to provide further data to constrain models of human depth interpolation. In our first experiment perceived depth was measured for the stimulus illustrated in figure 3a, where the rectangle is a uniform grey field, providing ambiguous depth information. Next, we examine the result of filling the rectangles with rivalrous texture (figure 3b). In such a rivalrous-texture stereogram the disparity cues are presented using monocularly defined edges (changes in contrast), while the texture elements (random dots) are uncorrelated between the two eyes. Finally, by filtering the uncorrelated random dots, we investigate the role of different spatial frequencies in depth interpolation.

2 Experiment 1

In the first experiment we assess the circumstances under which depth interpolation can be observed. In other words, we wish to determine the conditions under which the disparity of the edges in a stimulus controls the perceived depth of the intervening spatial locations. A simple stimulus which does not allow discrete point-by-point matching is a uniform rectangle where only the edges can be matched unambiguously. In this experiment we varied the contrast of the edges and the difference in edge disparity (disparity gradient). The independent manipulation of these two factors reveals whether there is an interaction between contrast and disparity gradient. In addition, we investigate interpolation given rivalrous texture in the rectangle.

2.1 *Method*

2.1.1 *Subjects.* Three subjects participated. Two were practiced observers, one was a graduate student naive as to the purposes of the experiment.

2.1.2 *Apparatus.* The generation and presentation of the stimuli was carried out with a Sun 3/160 computer. Stimuli were presented on the Sun color CRT screen using only the green gun of the monitor, and viewed through a Wheatstone-type stereoscope from an optical distance of 1 m. The left half-image on the screen was projected into the left eye, the right half-image into the right eye, and the disparity was crossed for all stereograms. The luminance of the screen was 0.1 cd m^{-2}, and room illumination was fairly dim.

2.1.3 *Stimuli.* The stimulus consisted of a rectangular field surrounded by a random-dot background (figures 3a and 3b). Each random dot was 5 min × 5 min square. The background was 6.7 deg × 6.7 deg in size. The mean luminance of the random-dot background was fixed at 17.2 cd m^{-2}, with grey levels ranging from 0.1 to 34.0 cd m^{-2}. These parameters were constant over all conditions.

The stimulus pattern, a 2.7 deg × 4.4 deg rectangle centered in the background, had zero min disparity at the left edge for all conditions investigated here. In this first experiment, the rectangle either was a uniform grey rectangle (figure 3a) or contained a rivalrous random-dot pattern (figure 3b). Four uniform-field conditions were investigated: the luminance was either 1.3 or 17.5 cd m^{-2}, and the disparity of the right edge of the rectangle was either 20 or 30 min. In the rivalrous condition, the rectangle and the background have the same luminance (17.2 cd m^{-2}). The rectangle was filled with 1 min × 1 min random dots, with luminance ranging from 0.1 to 34.0 cd m^{-2}. The random dots in the two half-images of the unfiltered stimulus had zero correlation and a Fourier spectrum which was flat up to 30 cycles deg^{-1}. For this condition, the edge disparity was 0 min for the left edge, and 20 min for the right edge.

(a)

(b)

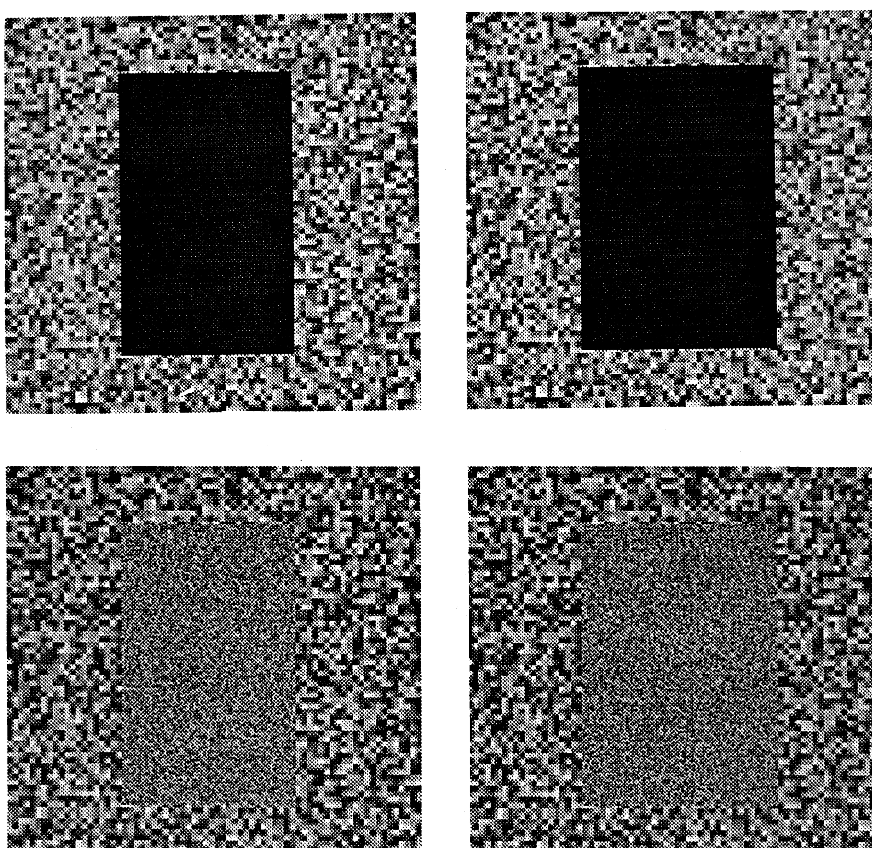

Figure 3. Stereograms used in experiment 1. (a) The uniform-field condition, where the stimulus rectangle is a uniform field on a random-dot background. The left edge has 0 min disparity, and the right edge has either 20 or 30 min disparity, when viewed from a distance of 40 cm. In the experiments, the stimuli had the same retinal sizes but were viewed from 1 m. (b) The rivalrous condition, where the rectangle is filled with random dots which are uncorrelated between the two eyes.

2.1.4 *Procedure.* The conditions were run in a randomized order using the method of constant stimuli. Each block began with the presentation of a fixation target that had zero disparity. A half-image of the stereoscopic fixation target consisted of an outline rectangle of the same size as the stimulus pattern. Next, the stimulus pattern was presented and remained displayed for the entirety of the block of trials. As soon as the stimulus pattern was fused, the subject initiated the first trial by pressing a 'mouse' button. On each trial, a test spot was briefly presented below the stimulus rectangle at one of three spatial locations: 40, 80, or 120 min from the left edge of the rectangle. This test spot was a 15 min × 46 min black rectangle. It was displayed for approximately 160 ms, which is about the latency for convergence eye movements (Rashbass and Westheimer 1961), in order to avoid eye movement strategies. Since the location of the test spot was chosen randomly, the subject could not converge to the depth plane of the test spot after its onset. Eye movements can and did occur, but were in no way correlated with the position of the test spot. The depth of ambiguous and rivalrous regions can be affected by convergence, and we did not want such effects to corrupt our results. The duration of the test spot varied somewhat since the experiments were run on a Unix system, but the variability of the duration was small ($\sigma < 10$ ms) and did not interfere with the results.

Subjects indicated with a button press whether the test spot was perceived in front of, or behind, the area of the rectangle lying immediately above it. The subjects were not given any further instructions as to which particular part of the rectangle the test spot should be compared. No feedback of any kind was given, since the task is inherently a subjective one and does not allow a classification of correct and incorrect responses. A new test spot was presented 1 s after the response. One block of trials consisted of four judgments of each of seven disparity values of the test spot for each of the three positions of the spot. The seven comparison disparities were separated by 1 min visual angle. These seven disparities were centered around a disparity which was estimated roughly in a pilot experiment for each subject using an adaptive staircase procedure to find the point of subjective equality. Within one block the stimulus pattern did not change and was presented continuously, whereas the test spot was manipulated in disparity and position and was flashed for approximately 160 ms. Positions and comparison disparities of the test spot were presented in random order.

2.2 *Results*

Figures 4–6 illustrate the main points. First, depth interpolation does occur with the type of stimulus used in this experiment. Second, the amount of interpolated depth depends critically on the contrast between stimulus pattern and background, and on the disparity of the edges (figure 4). Finally, depth interpolation is degraded when the area to be interpolated contains rivalrous texture (figure 6).

In figure 4, the perceived depth is given as a function of distance from the left (0 min disparity) edge of the rectangle. The rectangle had a width of 160 min, and the right edge had a disparity of either 20 or 30 min. The dotted lines indicate the perceived surfaces that would arise if the subject linearly interpolated between the two edges of the rectangle in the two disparity conditions. The perceived depth is shown measured at three intermediate positions. Each point is the mean of a psychometric function (the best-fitting cumulative normal distribution; Finney 1964, chapter IV). The vertical bars indicate two standard deviations of the mean. As we mentioned earlier, subjects report a percept of a tilted surface with the right edge coming out of the frontoparallel background plane.

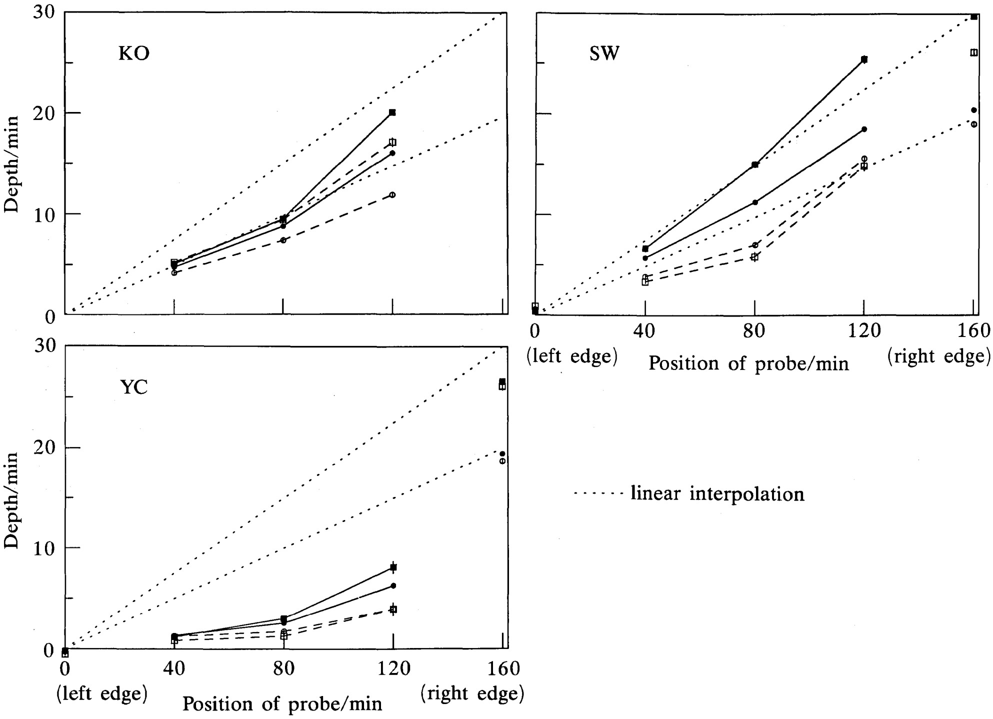

Figure 4. Interpolated depth for a uniform stimulus pattern as a function of probe (test spot) position in experiment 1. Solid lines and filled symbols are used for the high-contrast conditions; dashed lines and open symbols for the low-contrast conditions. Squares are used for the high disparity gradient (30 min at the right edge), and circles for the low disparity gradient (20 min at the right edge). Each point denotes the mean of a psychometric function. The length of the vertical bars corresponds to two standard deviations of the best-fitting cumulative normal distribution. Results are given for three subjects. Each data point is based on 224, 224, and 350 trials for subjects KO, SW, and YC, respectively. For subjects YC and SW the depth at the edges was also assessed using the method of constant stimuli and the same number of trials. Dotted lines give the linear interpolation based on the edge disparities.

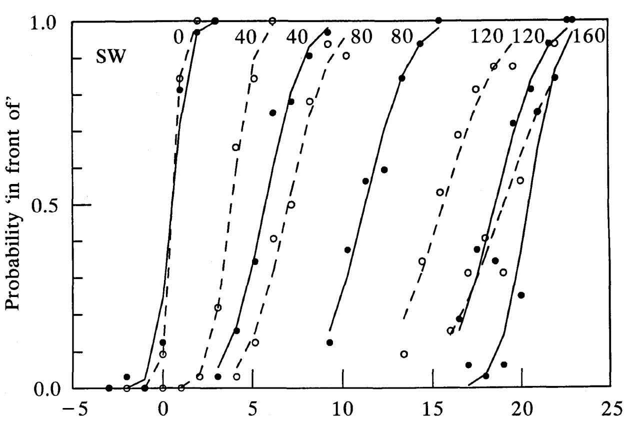

Figure 5. The effect of contrast on interpolated depth in subject SW. The psychometric functions for the low-disparity condition for all investigated positions (0, 40, 80, 120, and 160 min from the left edge are plotted. Best-fitting cumulative normal curves are given for each function. Open symbols and dashed lines denote the low-contrast condition, closed symbols and solid lines denote the high-contrast condition. Here, an increase in contrast results in a pure translation of the psychometric function, without a change in slope.

The influence of contrast on depth interpolation can be seen in figure 4 by comparing the solid and the dashed lines.[1] The solid lines connect the data obtained for the high-contrast conditions. The top solid curve results from a right-edge disparity of 30 min, and the lower solid curve for one of 20 min. Dashed lines connect data points obtained under the low-contrast condition. For all subjects the perceived depth is smaller when the contrast is low, although there is a large variability between subjects in the absolute perceived depth. However, the precision in the judgment is no worse for lower contrasts as long as the edge disparity is small. The loss in amount of depth only shifts the psychometric functions without changing their slope at all positions (figure 5). Finally, the amount of depth interpolation relative to a perfect linear interpolation is poorer for the larger disparity gradient (especially for subjects SW and YC). In other

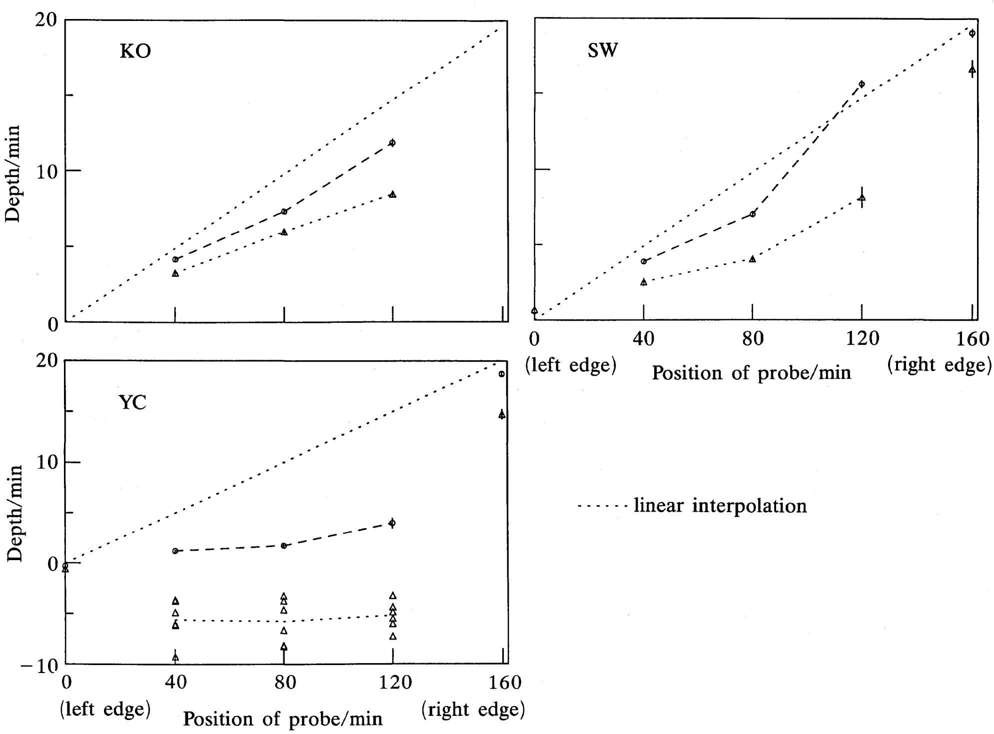

Figure 6. Interpolated depth for a stimulus pattern containing rivalrous texture as a function of probe (test spot) position in experiment 1. The rectangle is now filled with random dots which are uncorrelated between the two eyes. The curve for the low-contrast low disparity gradient uniform-field condition (dashed line connecting open circles) is replotted from figure 4 for comparison. For subjects KO and SW the method of constant stimuli was used. Each of the data points (open triangles) indicates the mean of a psychometric function (the best-fitting cumulative normal distribution) based on 224 trials. For subject YC, an adaptive procedure was used to assess the interpolated depth. Six staircases were randomly interleaved (two staircases for each of the three positions). Each data point (open triangle) indicates a single midrun estimate for the mean based on fourteen reversals. The dotted line joins the means of these estimates. For subjects YC and SW we also measured the perceived depth at the edges. The method of constant stimuli was used for both subjects and the estimated mean of the psychometric function is based on 224 and 350 trials for subjects SW and YC, respectively. Dotted line (no symbols) gives the linear interpolation based on the edge disparities.

[1] The effect of contrast on depth interpolation is very reliable. In a preliminary study we collected a much larger set of data for the low-disparity-gradient condition (1050 observations per datum point for subject SW and 350 observations for subject KO). There was a consistent difference between the low- and the high-contrast conditions.

words, the ratio between the depth predicted by a linear interpolation and the observed depth is always smaller for the large disparity gradient (right edge has 30 min disparity) than for the small disparity gradient (right edge has 20 min disparity). This holds for all investigated positions for both contrast values.

Inspecting the data of subject YC (figure 4) one might argue that the weak depth interpolation is due to a weak depth impression at the right edge (which had either 20 or 30 min disparity). This is not the case. We measured the depth at both edges as a control condition. The rightmost symbols in figure 4 indicate the perceived depth at the right edge of the rectangle, the leftmost symbols are the data points for the perceived depth at the left edge of the rectangle having zero disparity. Although the data exhibit the same pattern (low contrast results in weaker perception of depth and a relative decrease in perceived depth of the large disparity), they do not suffice to account for perceived depth at the intermediate spatial positions for subject YC. The perceived depth at the edges is almost 20 min for the low-disparity-gradient condition and approximately 25 min for the high-disparity-gradient condition. The intervening locations are perceived at a depth of less than 10 min. Thus it is not the case that interpolation is linear between the edges with the weak interpolation due to small perceived depth at the edges.

In figure 6 the results from the uniform-field condition are compared with perceived depth for a rectangle filled with random dots which are uncorrelated between the two eyes (ie rivalrous). The uniform-field condition plotted here had the same mean luminance and right-edge disparity as the random-dot pattern. Depth interpolation is substantially degraded with uncorrelated random dots (subjects KO and SW). For one subject (YC) the surface appears to lie far behind the background. Here, the interpolated depth was not assessed by the method of constant stimuli, but rather by using an adaptive procedure (Levitt 1970). The adaptive assessment was necessary because of the large variability in the data from session to session, which did not allow us to use fixed comparison stimuli. Each point is the average of two misrun estimates based on randomly interleaved staircases. A midrun estimate is provided by averaging over all the peaks and the valleys in all the separate staircase runs.[2]

2.3 *Discussion*

From figures 4 and 6 we conclude that perceived depth is not necessarily a simple linear interpolation between two well-defined depth values. Given a fixed disparity gradient, the interpolated depth is greater for larger contrasts. Grossberg's theory (Grossberg 1987, page 131) allows for an interaction between depth and brightness information and could, in principle, qualitatively predict a contrast dependence of interpolated depth. From the data illustrated in figure 4 one might conclude that strong edges or contours play a crucial role in depth interpolation. We pursued this idea by generating stimuli with blurred or interrupted horizontal edges (the top and bottom edges of the stimulus rectangle), leaving the left and right disparity-producing edges intact. Our informal observations do not support this hypothesis. Depth interpolation does not seem to be degraded by blurred horizontal edges or by small gaps interrupting the horizontal edges. This is true even though these stimuli did not produce strong illusory contours at the breaks.

Figure 4 reveals that the interpolated depth does not increase proportionally with the disparity gradient. Compared to a linear interpolation, perceived depth is relatively poorer for the high disparity gradient (30 min disparity at the right edge) than for the low disparity gradient (20 min disparity at the right edge).

The interpolated depth at the position which is the most distant from either of the two edges (ie farthest from positions at which depth is well-defined) is less than

(2) For further discussion see, for example, Falmagne (1985, page 225).

expected by a linear interpolation defined by the leftmost and rightmost investigated positions. In other words, the surface describing interpolated depth is curved. Also, contrast and disparity gradients are not independent. The reduction in perceived depth as contrast is reduced is particularly strong for a high disparity gradient (at least for subjects SW and YC).

When the rectangle is filled with rivalrous texture, depth interpolation is further degraded (figure 6). One subject (YC) even perceived the region between the two edges as lying behind the zero-disparity background. This depth percept has been reported for random-dot stereograms consisting of a region of uncorrelated dots superimposed on a correlated surround (Julesz 1960, citing Wegner 1959). A recent study by O'Shea and Blake (1987) reveals the same phenomenon: when subjects were exposed dichoptically to a region of uncorrelated dots superimposed on a zero-disparity random-dot background, they perceived a rivalrous central region situated behind a fused surround (O'Shea and Blake 1987, figure 5). Clearly, for subject YC the disparity values of the two edges did not influence the depth assigned to the intermediate locations. The percept is solely governed by the fact that the stimulus is rivalrous. A less dramatic loss in interpolation occurs for the other two subjects. The disparity of the left and the right edge determines, to some extent, the depth of the intervening points. This influence is considerably weaker than for the uniform field. Marked individual differences in the perceived depth of uncorrelated random-dot patterns have been reported by Holliday and Braddick (1985).

We wish to point out that the interpolation observed for uncorrelated random dots is not due to a deficiency in spatial resolution. This is easily demonstrated by presenting a region of *correlated* dots of the same dot size as in the uncorrelated case. With such a stimulus the dots are matched point-by-point and a horizontal plane is perceived at the appropriate depth. There still remains a monocularly defined edge (the central region still has a different dot size from the background). The right-hand edge of this monocularly defined region has a non-zero disparity and is perceived as a single vertical edge floating in depth above a flat ground. Obviously, in this case all the random dots can be matched consistently in a discrete fashion and the disparity of the monocularly visible edges plays no role in the assignment of depth values to the intervening points.

This might lead one to conclude that point-by-point matching is always performed if possible, and that depth defined by point-by-point matching has a larger impact on the final depth value than depth derived from the depth of neighboring spatial locations (interpolated depth). However, there are counterexamples. Mitchison and McKee (1987) have shown that there are cases where it is possible for globally consistent matches to be ignored. They investigated stereograms consisting of regularly spaced points. In these stereograms point-by-point matching was always possible. They found that if the stereogram was presented as a series of brief flashes (each flash 160 ms, for a total viewing time of 2 – 3 s) the perceived depth was interpolated between the edges of the stereogram. This interpolated depth overrode discrete matching.

Two factors may have caused the failure of depth interpolation with the uncorrelated dot pattern: rivalry and weakly defined edges. The edges of the rectangular region were only defined by a change in dot size, not by a change in mean luminance across the edge. In other words, across this edge the average contrast was zero. On the other hand, reasonably strong depth interpolation was measured for the low-contrast uniform-field conditions (figure 4, open symbols), for which the average contrast across the edge was also approximately zero. Therefore, we feel that it is the rivalry that is causing the failure of interpolation. However, in order to avoid this problem of confounding texture information with edge information, a uniform background was used in experiment 2 so that edges were always equally salient in all conditions of that experiment.

3 Experiment 2

In the first experiment we demonstrated that depth interpolation is degraded, but still occurs (for subjects SW and KO), if the region to be interpolated consists of random dots uncorrelated between the two eyes. Informal observations revealed that enlarging the random dots degrades depth interpolation further. Since the total contrast energy of the uncorrelated pattern does not change when dot size is increased, one might argue that the additional contrast at low spatial frequencies is responsible for this further decline in interpolation. The problem with this reasoning is that it does not take into account the variation of human contrast sensitivity with spatial frequency.

In experiment 2 we investigate the relative strength of different spatial frequencies for degrading depth interpolation. This was tested directly by bandpass filtering the random-dot patterns used to fill the stimulus rectangles. Again, the textures were uncorrelated between the two eyes. The narrow-band patterns were matched in perceived contrast to allow for comparisons between different passbands. We varied both spatial-frequency content and perceived contrast in order to determine which factor is most salient.

3.1 *Method*

The apparatus, subjects, and stereogram geometry were identical to those of experiment 1.

3.1.1 *Stimuli.* The stimuli (figure 7) consisted of rectangles of filtered texture on a zero-disparity background. The background was uniform (13.5 cd m^{-2}), and surrounded by a zero-disparity frame of random dots in order to provide some strong zero-disparity cues. The stimulus pattern, a rectangle centered in the background, had 0 min disparity at the left edge and 20 min disparity at the right edge. The textures used for the stimuli were spatially bandpass filtered random-dot patterns. The stimulus had monocularly defined luminance edges carrying a certain disparity, but the region between these two edges was made of texture which was uncorrelated between the two eyes. The maximum frequency (for unfiltered 1 min random dots) was 30 cycles deg^{-1}. The mean luminance of the stimuli was kept constant at approximately 17 cd m^{-2}.

Four different bandpass filters were used, with passbands centered at 2, 4, 8, and 16 cycles deg^{-1}. Bandwidth at half-height was one fifth of the center frequency. A 10th order Butterworth filter was used. Stimuli were processed using the HIPS image processing software (Landy et al 1984). Representative stimuli are pictured in figure 7. A control condition was also run where the rectangle was simply a uniform field with luminance equal to the mean luminance of the texture conditions.

We investigated two levels of perceived contrast. Since contrast sensitivity varies with spatial frequency, it was necessary to match the four narrow-band noise stimuli in contrast. This was accomplished by fixing the contrast for one passband, and letting the subject match this stimulus with the other stimuli with respect to perceived contrast. One contrast level was such that the stimulus centered at 16 cycles deg^{-1} was approximately fifty times its detection threshold and all other passbands were equivalent in apparent contrast; the other contrast level was chosen such that the 8 cycles deg^{-1} stimulus was approximately one hundred times its detection threshold. In the latter case only three passbands were used, since this high perceived contrast level was not realizable for the 16 cycles deg^{-1} stimulus. In order to express the contrast of the narrow-band noise stimuli as multiples of a typical detection threshold, we refer to the detection threshold data from van Nes and Bouman (1967). These detection data were measured using gratings, but similar data are to be expected from filtered noise (Mostafavi and Sakrison 1976).

The contrast matches were obtained by means of an adaptive procedure. Two staircases converging to the point of subjective equality were randomly interleaved for each of the three spatial frequencies to be matched. The final estimate is the average of these two means. The contrast matches were performed for each subject individually and the random texture patterns used for the second experiment were adjusted in contrast for each subject according to the result of the matching procedure.

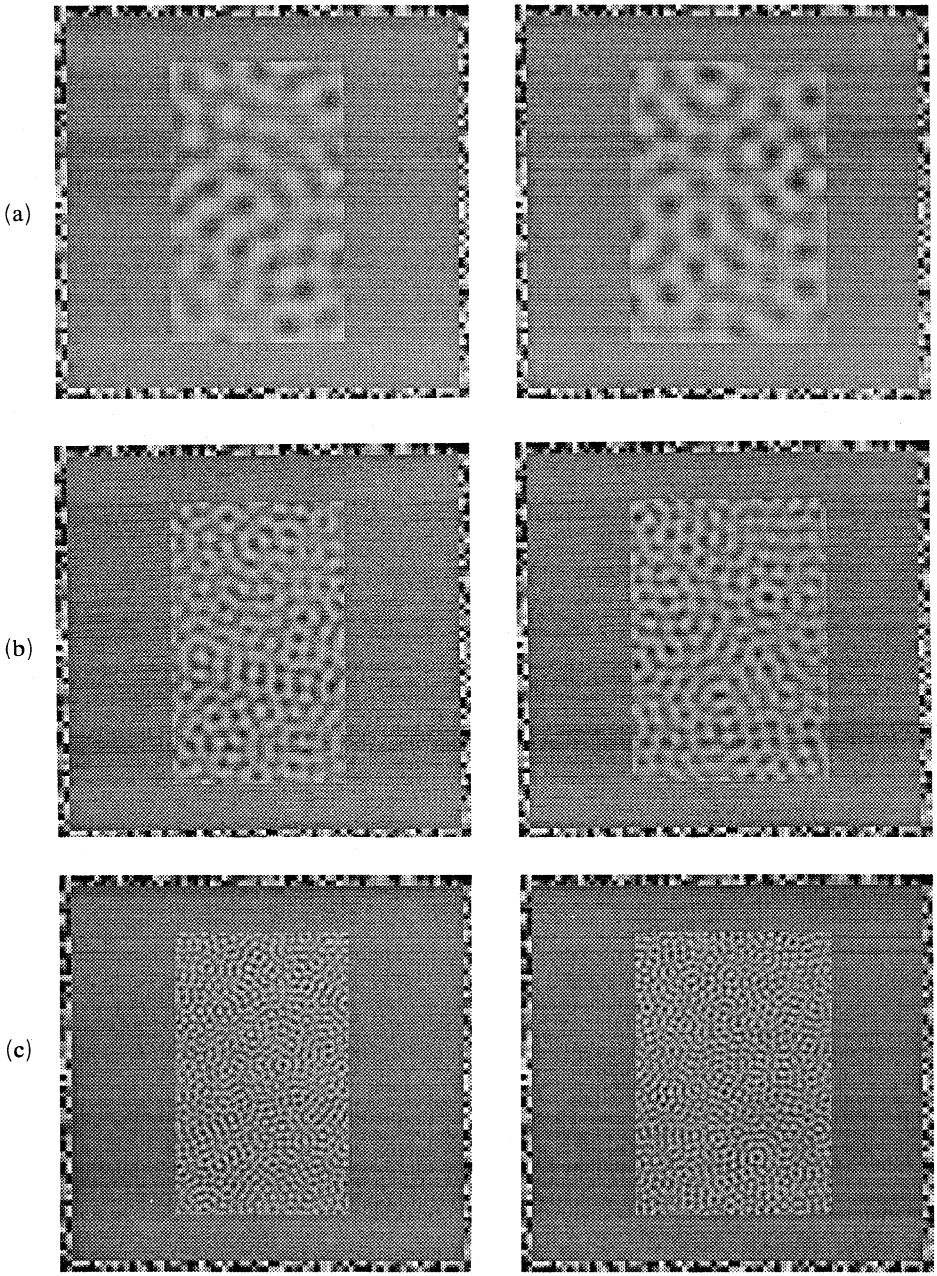

Figure 7. Narrow-band noise stimuli used in experiment 2. A 10th order Butterworth filter was applied to a random-dot field to produce the texture in each rectangle. Bandwidth at half-height is one fifth of the center frequency. For the high-contrast level only three center frequencies were used: (a) 2 cycles deg^{-1}, (b) 4 cycles deg^{-1}, and (c) 8 cycles deg^{-1}, viewed from a distance of 40 cm. In the experiments, the stimuli had the same retinal sizes but were viewed from 1 m. Each center frequency (except 16 cycles deg^{-1}) was investigated at two contrast levels.

Eight conditions were investigated. At the lower perceived contrast level all four narrow-band noise patterns were used, with the passband centered at 2, 4, 8, and 16 cycles deg^{-1}. At the high-contrast level only the patterns centered at 2, 4, and 8 cycles deg^{-1} could be realized. A uniform rectangle with the same mean luminance as the noise patterns served as a control stimulus.

3.1.2 *Procedure.* The experimental procedure was similar to that used in experiment 1. In this experiment an adaptive procedure was used to assess the interpolated depth. This turned out to be necessary because of the large variability observed in a preliminary experiment.

To ensure that the data obtained by the two-alternative forced-choice (2AFC) paradigm reflect the percept and are not an artifact of the procedure, the stimuli were presented to seven subjects, including the three participants in the 2AFC procedure. Three of the other four subjects were naive to the purpose of the experiment. Informal reports on the perceived depth were gathered. All subjects were tested for normal stereovision by presenting an ordinary random-dot stereogram.

3.2 *Results*

The results for the three subjects are shown in figure 8. The data are average midrun estimates based on an adaptive procedure. In each block six staircases were randomly interleaved: two for each of the three investigated positions. The data points denote averages of two midrun estimates of the mean. The stopping criterion used for each single staircase was twelve reversals. The starting values were the same for all three positions; one staircase had a low initial disparity value and the other started with a large disparity for the comparison stimulus. The step size was reduced as the number of reversals increased. On average, one condition required 132 trials for subject KO, 157 trials for subject YC, and 117 trials for subject SW.

Although there is a large variability between subjects, all data exhibit the following two properties. First, noise patterns limited to a low-spatial-frequency band (centered at 2 cycles deg^{-1}; denoted by downward-pointing triangles in figure 8) are always perceived as near or even behind the zero-disparity background, whereas high-spatial-frequency stimuli (8 and 16 cycles deg^{-1}; upward-pointing triangles and circles, respectively) are always seen at a depth plane near or in front of a linearly interpolated surface. Second, not only is the interpolated surface shifted in depth depending on frequency content, but also the perceived slant of the surface is decreased for low-spatial-frequency stimuli. The highest variability between subjects is observed for moderate spatial frequencies (4 cycles deg^{-1}; squares). For the control stimulus (uniform field; crosses connected by solid line) all subjects overestimate the depth of the inner region slightly relative to a linear depth interpolation.

3.3 *Discussion*

The first point worthy of emphasis is that the data obtained by the 2AFC procedure are in agreement with the informal reports of the seven subjects. Since the three subjects participating in the 2AFC procedure were instructed to judge the depth of the texture (filtered random dots), one percept consistent for all subjects is not reflected in the data. For the low-spatial-frequency textures (2 cycles deg^{-1}) a transparent tilted plane was perceived, interpolated between the two edges.[3] The texture was described as lying behind the transparent plane, or even behind the background (for 2 cycles deg^{-1}). The texture was perceived as flat or only weakly tilted. The same effect occurred for the

[3] The percept of a transparent plane is enabled by the difference in mean luminance between the noise pattern and the background. For stimuli with no luminance difference no transparency is perceived, but the depth assigned to the low-spatial-frequency texture remains the same.

intermediate spatial frequency (4 cycles deg^{-1}), although more weakly.[4] For high spatial frequencies (8 and 16 cycles deg^{-1}), subjects never reported transparency. The texture was perceived as tilted in a manner similar to the uniform-field condition. For low spatial frequencies the interpolated region was sometimes perceived as curved. Depth interpolation of patterns limited to high spatial frequencies was always described as linear. High-spatial-frequency rivalrous textures were never perceived as lying behind the zero-disparity background. Filtered textures at a high level of perceived contrast were usually described as unstable.

The important point of the data in figure 8 is the relation between depth interpolation and spatial-frequency content of the uncorrelated noise pattern. Although subjects usually found it more difficult to judge the depth for the high-contrast stimuli

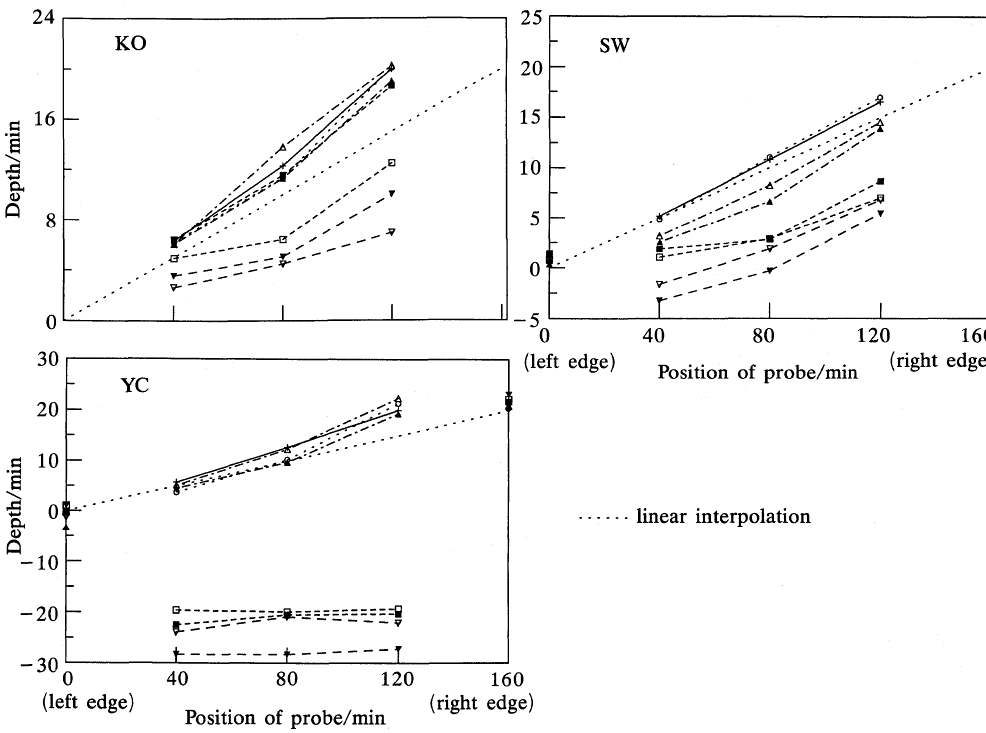

Figure 8. Interpolated depth for narrow-band noise stimuli as a function of probe (test spot) position in experiment 2. The parameter of each curve is the center frequency of the narrow-band noise stimulus and the perceived contrast. The different passbands are matched in apparent contrast. Open symbols refer to stimuli with low contrast, closed symbols indicate that the contrast level is high. Four noise bands were used, centered at 16 cycles deg^{-1} (circles and dotted lines), 8 cycles deg^{-1} (upward-pointing triangles and dot–dashed lines), 4 cycles deg^{-1} (squares and short-dashed lines) and 2 cycles deg^{-1} (downward-pointing triangles and long-dashed lines). The crosses connected by the solid line are data for the control condition, in which a uniform rectangle with the same mean luminance as the narrow-band noise stimuli was used. Interpolated depth was assessed with an adaptive procedure. Each data point is the average of two midrun estimates adopting twelve reversals as the stopping criterion. Data for three subjects are shown. The average number of trials required per point is 132, 117, and 157 for subjects KO, SW, and YC, respectively. For subjects YC and SW the perceived depth at the edges was assessed in addition to the intermediate depth values.

[4] A strong impression of a transparent plane is equivalent to a clear separation between the texture and a plane interpolated through the edges. To perceive transparency implies that the texture (filtered random dots) is seen in a depth plane behind the plane defined by linear interpolation.

because of binocular rivalry, there is no effect of perceived contrast consistent for all subjects. Figure 8 illustrates a clear effect of spatial-frequency content, despite the fact that there is a large variability between subjects. Patterns band-limited to low spatial frequencies (2 cycles deg^{-1}) are consistently perceived as flatter and sometimes as lying (or starting) behind the zero-disparity background (subject SW). Noise stimuli containing only high spatial frequencies (8 or 16 cycles deg^{-1}) are always perceived as above the background, and usually yield the same percept as the uniform field.

The percept of a transparent plane, as found for the low-spatial-frequency pattern, suggests that different spatial-frequency bands are processed separately from each other. Grossberg's model (Grossberg 1987, page 132) operates on multiple spatial scales and transparency phenomena are explained by filling-in reactions across some, but not all, of the different spatial scales. In particular, differential filling-in allows for filling-in at different depth planes as long as the individual scales are associated with different depth values. Thus, a qualitative explanation of our results may be possible using this model.

Parish and Sperling (1987) found that in an object recognition task the object spatial frequency (ie cycles $object^{-1}$) rather than the retinal spatial frequency (cycles deg^{-1}) determined identification efficiency. Considering these findings one might ask whether interpolation is affected by retinal or object spatial frequencies. Our informal observations (varying viewing distance for our stimuli) suggest that retinal spatial frequency is the relevant variable for degree of interference of rivalrous material with depth interpolation.

Frisby and Mayhew (1978) investigated the relationship between apparent depth and disparity in rivalrous-texture stereograms. Using a stimulus with uncorrelated surround and uncorrelated central regions differing in spatial frequency, they demonstrated that the perceived-depth–disparity relation depended on the spatial-frequency content of the two regions. A noise pattern centered at a high spatial frequency (10 cycles deg^{-1}) on a surround containing only low spatial frequencies (center frequency at 2.5 cycles deg^{-1}) resulted in a larger perceived depth of the central region than for a 2.5 cycles deg^{-1} central region presented on a 10 cycles deg^{-1} surround (Frisby and Mayhew 1978, figure 2). In contrast to this, if the disparity of the central region (defined by the monocularly discriminable luminance edges) was zero, a central region limited to low spatial frequencies (2.5 cycles deg^{-1}) was perceived as lying behind a high-frequency background (10 cycles deg^{-1} pattern). These results are consistent with our finding that patterns limited to low spatial frequencies appear to recede in depth.

Experiments by Schor and Howarth (1986) and Brown et al (1986) reveal that this depth bias occurs under binocular and monocular viewing conditions. Presenting spatially filtered vertical bars dichoptically, Schor and Howarth (1986, figure 5) found a perceived depth bias for low spatial frequencies (below 1.2 cycles deg^{-1}) in the uncrossed direction. This depth bias also occurred monocularly, but was always greater when viewed binocularly (with zero disparity). The same perceived depth bias under monocular viewing conditions was reported by Brown et al (1986). They found that low-spatial-frequency textures are perceived as the ground to figures with higher spatial frequency; low-spatial-frequency patterns appear more distant and high-spatial-frequency textures appear to be closer in depth.

4 Conclusions

We have investigated the simplest case of depth interpolation where only the two vertical edges of a rectangle provide well-defined disparity values. We find that depth interpolation occurs given this sparse disparity information. There are three main points.

(i) If the region to be interpolated is ambiguous, as in the case of a uniform rectangle, depth interpolation occurs. Interpolated depth is larger for greater contrasts between rectangle and background. Relative to a linear interpolation between the two vertical edges, depth interpolation is poorer for greater edge disparities. The percept is of a tilted rectangle with the right edge coming forward to the observer.
(ii) Depth interpolation is degraded if the region between the two vertical edges contains rivalrous information, as in the case of uncorrelated random dots.
(iii) More specifically, the loss in depth interpolation can be accounted for by rivalrous information at low spatial frequencies. If the rivalrous texture consists entirely of low spatial frequencies with an additional difference in mean luminance between the rectangle and the background, subjects perceive a transparent plane passing through the two vertical edges of the rectangle. The texture defined by the low-spatial-frequency content of the image is seen as lying behind this linearly interpolated transparent plane. Rivalrous high-spatial-frequency content does not interfere with interpolation. It yields a percept similar to the uniform-field condition.

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