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D_{max} for Stereopsis Depends on Size, Not Spatial Frequency Content

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Stereoacuity depends not only on the carrier frequency of Gabor stimuli, but also upon their size. To determine if this is also the case at large disparities, we have measured the upper limit for stereopsis, "D_{max}", and assessed its dependence on carrier frequency and overall envelope size. The results differ markedly from the stereoacuity data. D_{max} for stereopsis is primarily dependent on the *size* of the envelope of the Gabor patch, and is relatively independent of its carrier frequency. These results support the proposition that stereopsis is achieved at large disparities by way of non-linear processing (envelope extraction).

Stereopsis D_{max} Size Spatial frequency Non-linear

INTRODUCTION

In a recent set of experiments (Hess & Wilcox, 1994) we assessed the type of spatial filtering underlying stereoacuity for band-limited Gabor stimuli. Specifically, we wished to know whether the Gaussian envelope of such a stimulus was used in its depth localization, as it is in its two-dimensional localization (Toet, 1987; Toet & Koenderink, 1988; Kooi, DeValois & Switkes, 1990; Hess & Holliday, 1992). Our results suggest that stereoacuity is determined by the carrier spatial frequency for spatially broadband stimuli, but by the Gaussian envelope for spatially narrowband stimuli. Thus there is evidence for both early linear and non-linear operations in the processing of small disparities within the fusion range. Given these results for stereoacuity, we now ask whether a similar filter duality is present for large disparities *outside* the fusion range.

There is a long history of interest in "coarse stereopsis" or depth perceived at large stimulus disparities (Tschermak & Hoefer, 1903, cited in Ogle, 1953; Mitchell, 1969; Ogle, 1953; Westheimer & Tanzman, 1956; Blakemore, 1970; Richards & Kaye, 1974; Krekling, 1975; Kaye, 1978; Schor & Wood, 1983; Schor, Wood & Ogawa, 1984). Ogle (1953) observed that there is "no evident change in the trends of stereoscopic sensitivity with angular disparity in the transition from fused images to double images" (Ogle, 1953, p. 910). Consistent with Ogle's (1953) observation, was Richards and Kaye's (1974) proposal that the distinction made between local and global stereopsis† is an artifact of the stimulus used to assess stereopsis. They noted that in earlier experiments, large stimuli were employed at large disparities and small stimuli were employed at small disparities. To separately evaluate the effects of size and disparity they asked subjects to rate the perceived depth of bars of different widths, presented at a number of disparities. Richards and Kaye (1974) reported that there exists a "depth continuum", for at each bar width the perceived depth increased smoothly with increasing disparity up to a maximum, and then returned to zero. Furthermore, it is evident from an analysis of their data that the disparity at which the percept of depth disappeared increased proportionately with bar width up to the largest bar width of 0.8 deg (slope of approx. 1 on log–log axes).

To investigate the effect of spatial frequency on the disparity range for stereopsis, Schor and Wood (1983) measured the upper limits for stereopsis using difference-of-Gaussian (doG) stimuli. They measured the upper disparity limit (D_{max}) for a range of stimulus sizes for crossed and uncrossed disparities. Using the method of adjustment, with unlimited viewing time, they reported that D_{max} was constant for spatial frequencies > 2.4 c/deg and increased as spatial frequency decreased with a slope of 0.5.

Although both Richards and Kaye (1974), Schor and Wood (1983) and Schor *et al.* (1984) examined the effects of size and spatial frequency on D_{max}, in each study the spatial frequency content of the stimuli covaried with changes in size, and vice versa. Thus, it is not possible to determine from their data whether changes in the upper limits of stereopsis were due to the changes in size,

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†Richards and Kaye (1974) use the terms local and global stereopsis to refer to stereopsis at small (15 arc min) and large disparities, respectively. However, the terms local and global stereopsis have since acquired quite different meanings (Tyler, 1983). To avoid confusion, throughout this paper we will refer to the depth produced by small and large disparities as fine and coarse stereopsis, respectively.

changes in spatial frequency content, or some combination of the two. To separately assess the effects of these two variables on D_{max}, we report here the results of experiments in which D_{max} was measured using spatial-frequency band-limited Gabor stimuli. Because it is possible to separately vary the size of the Gaussian envelope and the spatial frequency of the carrier grating, this is an ideal stimulus for disassociating their effects.

The effect of contrast on stereoacuity has been measured in a number of studies, all of which have reported that stereoacuity increases with the square root of the suprathreshold contrast (Legge & Gu, 1989; Halpern & Blake, 1988; Cormack, Stevenson & Schor, 1991; Hess & Wilcox, 1994). To our knowledge there are no published accounts of the contrast dependence of the upper limits of stereopsis. If disparity range and spatial filter properties covary as some theories of stereopsis suggest (Ohzawa, DeAngelis & Freeman, 1990) then one would expect that D_{max} and stereoacuity should exhibit a similar dependence on stimulus contrast. However, if large and small disparities are conveyed by separate mechanisms then their contrast dependence may differ.

METHODS

Subjects and apparatus

Extensive measurements were obtained using two experienced subjects. Both subjects wore their prescribed optical correction and had normal stereopsis as evidenced by "perfect" Randot Stereotest scores of 20 sec and, perhaps more convincingly, by their previous performance in stereoacuity experiments under a variety of viewing conditions.

Stimuli were presented on a Joyce Electronics display screen with a P31 phosphor. The display was refreshed at 200 Hz, and had a vertical 100 kHz raster. The dimensions of the display area were 29 × 22.5 cm. The mean luminance of the display was approx. 45 cd/m^2 when viewed through the liquid crystal shutters that were used to produce stereoscopic depth. A $\pm$10 V signal, supplied via a digital to analogue port, controlled the state of the shutters and was synchronized with the onset of each frame of the Joyce display. The stimuli for each eye were presented on alternate frames at a rate of 100 Hz per eye. The reference stimuli were presented with zero disparity on all trials, while the target patches viewed by the two eyes were offset in equal and opposite directions, by the amount required for each test condition.

Stimulus contrast was controlled by varying a (14-bit) voltage from the digital signal generator and multiplying it with the Gabor stimuli output from graphics memory, the contrast of which could also be scaled (8-bit resolution). This provided accurate estimates of contrast threshold as the Joyce display screen has a linear Z-amplifier. The stimuli were patches of sinusoidal grating multiplied by a symmetric two-dimensional Gaussian (Fig. 1). The grating component of each stimulus was oriented vertically. The form of the Gabor function was:

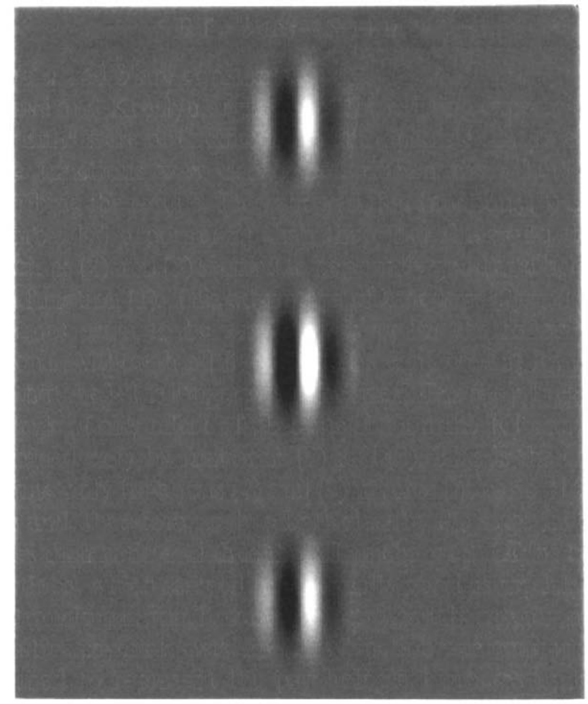

FIGURE 1. Shown here is the stimulus arrangement used to assess the upper limits for stereopsis. Three Gabor patches were vertically oriented and aligned, and presented simultaneously. The two peripheral patches provided the fixation plane, while the centre target was displaced in depth. Depth was generated by introducing equal and opposite shifts to the monocular images of the centre target. On each trial, subjects gradually increased the disparity in the monocular images of the centre target until the sensation of depth was lost.

$$G(x,y) = A * \sin(2\pi x/T)\ \exp(-(x^2+y^2)/(2\sigma^2)) \quad (1)$$

where A is the amplitude of the function, σ is the standard deviation of the Guassian envelope defining the patch and T is the period of the carrier grating. Since the carrier was in sine phase with the envelope there was no mean luminance component in the stimulus.

All three Gabor stimuli were presented simultaneously within a temporal raised cosine of 1 sec total duration, which meant that the stimulus was visible for approx. 0.33 sec. Previous stereoacuity experiments performed with these stimuli (Hess & Wilcox, 1994) showed no effect of separation for the relatively broad bandwidth Gabors used here. Therefore we selected an intermediate degree of separation at which subjects reported that the reference patches provided a strong fixation plane. The separation between the reference and central Gabors was held constant at 4 times the standard deviation of the Gaussian envelope, thus the separation distance varied from 6.0 to 0.38 deg at 0.25 and 4.0 m respectively. The size and spatial frequency of the patch were manipulated by changing the viewing distance to the screen, or by changing the appropriate parameters in the equation used to generate the Gabor patches.

Procedure

In all the experiments reported here, we measured the disparity at which the central Gabor patch could

TABLE 1. Sample contrast threshold values* for subject LMW, since thresholds were measured at the start of every session, each value represents the average of several measurements

Viewing distance		Period				Envelope size			Contrast	
m		Lines/c	0.5 m	1.0 m	2.0 m	Arc min	1.31 c/deg	0.66 c/deg	m	
0.25	0.065	5	0.33	0.03	0.039	45.8	0.054	0.06	0.5	0.05
0.5	0.04	10	0.08	0.025	0.45	22.9	0.08	0.03	1.0	0.04
1.0	0.03	20	0.05	0.444	0.02	11.45	0.11	0.06	2.0	0.02
2.0	0.25	50	0.06	0.055	0.04	5.73	0.13	0.11	4.0	0.09
4.0	0.26	100	0.12	0.43	0.49					
		300	0.26	0.30	0.22					

*Michelson contrast: $\frac{L_{max} - L_{min}}{L_{max} + L_{min}}$ where L_{max} = maximum luminance and L_{min} = minimum luminance.

no longer be localized in depth relative to two identical peripheral patches which formed the fixation plane. The two reference stimuli were located directly above and below the stereo-target (Fig. 1) and provided a rich fusion and reference stimulus. Additional nonius lines or fusion aids were not added to the display primarily because in our previous stereoacuity experiment we did not use nonius lines. Since we were interested in comparing the results of these experiments, we kept the display as similar as possible. The participants in this experiment were highly practiced observers and had no difficulty fusing the reference stimuli. The subjects' reports of stable fixation are confirmed in the data by the very small standard errors obtained for all test conditions (in most cases standard errors are much smaller than the symbols used).

D_{max} was measured using the method of adjustment; the stimulus disparity was gradually increased in 1 pixel steps from near zero disparity, until the upper limit for stereopsis was reached. The angle subtended by 1 pixel varied with viewing distance such that at 0.25, 0.5, 1.0, 2.0 and 4.0 m, 1 pixel equaled 9.16, 4.58, 2.29, 1.145 and 0.57 arc min respectively. The starting disparity for the method of adjustment was varied randomly by several pixels on separate trials to ensure that a constant number of responses was not required to reach D_{max}. Subjects were told to attend to the reference patches to maintain vergence on the zero disparity plane, but were able to move their eyes about the display. On any given trial, subjects indicated when the diplopic stimulus returned to the fixation plane by pressing the appropriate button on a Logi-Tech mouse.

Complete measurements were made for crossed disparities only. However, given that crossed and uncrossed disparities may be processed by different mechanisms (Richards, 1971; Poggio & Fischer, 1977) we measured the performance of one subject for all conditions using uncrossed disparities. The results of this control study showed that performance was the same regardless of the direction of the depth displacement. In an additional experiment (reported in the Results) we found that JH does have a systematic bias. That is, she consistently reaches her upper disparity limit at smaller uncrossed than crossed disparities. Importantly, the form of the data is the same for both displacement directions.

Prior to testing, contrast thresholds were determined for the peripheral stimuli (with central fixation), for all conditions. The method of adjustment was used to obtain seven threshold determinations which were averaged to provide the final estimate. Subsequently, the contrast of all three patches was set to be 8 dB above this threshold value for each stimulus (see Table 1 for example contrast thresholds for LMW). In each session a total of 10 estimates of D_{max} were obtained, and then averaged, to provide a final D_{max} estimate.

In separate sessions we assessed four independent variables. First, we measured the contrast dependence of the upper limits for stereopsis. Next, D_{max} was recorded at a range of viewing distances in order to scale the size and centre spatial frequency of the Gabor. In the third study, we held the size of the Gabor patch constant, but varied the spatial frequency of its carrier. Finally, we changed the size of the Gabor patch, while holding the carrier frequency constant. In the Results we also describe two control experiments in which we used an interleaved staircase procedure to measure D_{max}. The first of these replicates the results obtained in the first set of experiments, and the second examines the effect of target-reference separation on the upper disparity limit.

RESULTS

In the first experiment, we assessed the effect of varying stimulus contrast at fixed levels above the individual contrast thresholds for our stimuli. At each of four spatial frequencies (0.66, 1.31, 2.62, and 5.24 c/deg), a range of 5–7 suprathreshold contrast values were tested. D_{max} is displayed in Fig. 2 for two subjects (subject JH was not tested at 5.24 c/deg) as a function of contrast (plotted in dB, where 20 dB = 1 log unit above threshold). The data show that at each spatial frequency tested there is no effect of Gabor contrast on D_{max}, even at contrasts as low as 3 dB (a factor of 1.41) above detection threshold. These results for D_{max} differ markedly from those previously reported for stereoacuity where there is a square root contrast dependence (Legge & Gu, 1989; Halpern & Blake, 1988; Cormack *et al.*, 1991; Hess & Wilcox, 1994).

Next, we assessed the effect on D_{max} of scaling the Gabor patches. Five viewing distances were tested: 0.25, 0.5, 1.0, 2.0 and 4.0 m, so that the spatial frequency and

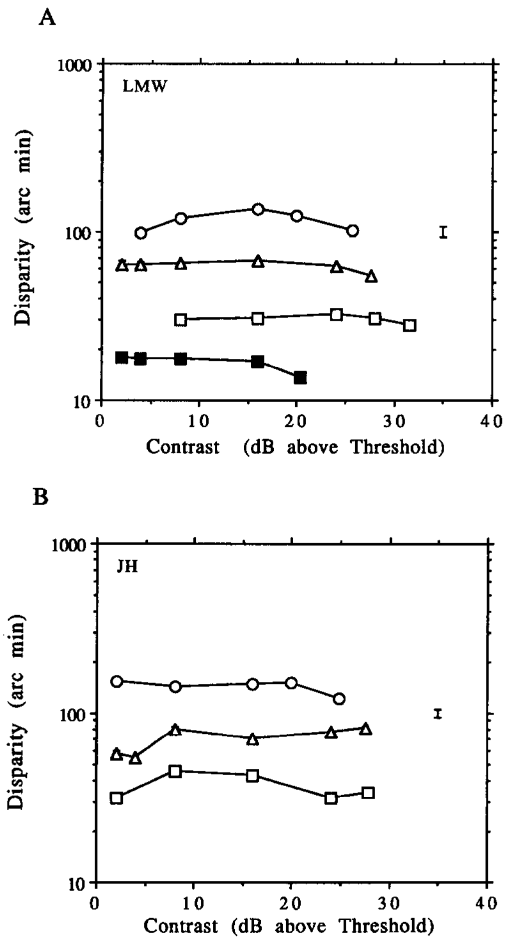

FIGURE 2. The upper limits for stereopsis (D_{max}) are shown here for two subjects. Three carrier spatial frequencies, 0.66 c/deg (○) 1.31 c/deg (△) and 2.62 c/deg (□) were tested at a range of contrasts from approx. 3 dB above contrast threshold, to the maximum contrast available. Subject LMW was tested at an additional spatial frequency of 5.24 (■) c/deg. Error bars to the right indicate the maximum SEM for the data shown here.

Gaussian envelope size scaled from 0.33 c/deg, $\sigma = 91.6$ arc min to 5.24 c/deg, $\sigma = 5.73$ arc min. D_{max} decreased monotonically with increasing viewing distance. As shown in Fig. 3 the slope on log–log axes is approx. -1 for both subjects' data.

In the preceding experiment, scaling the stimuli produced variations in both size and carrier spatial frequency. In the subsequent experiments, we determined the relative effects of these two variables. In Fig. 4(A, B) we have plotted D_{max} for a range of carrier frequencies, for each of four envelope sizes ($\sigma = 45.8$, 22.9, 11.45 and 5.73 arc min).

There is a slight decrease in D_{max} with increasing spatial frequency for some of the functions.* However, this weak effect cannot account for the more pronounced decrease in D_{max} that occurs with increased viewing distance. The vertical displacement of the data for the four different envelope sizes suggests that reducing the envelope size may have a more significant impact on D_{max}.

To evaluate this possibility, we manipulated the size of the Gaussian envelope while holding the carrier frequency constant. The size of the Gaussian envelope ranged from $\sigma = 45.8$–5.73 arc min, while the spatial frequency of the carrier was held constant at either 1.31 or 0.66 c/deg. The results of this experiment are displayed in Fig. 5(A, B). As suggested by the results of the previous experiment, D_{max} is strongly influenced by changes in envelope size. The effect of envelope size on D_{max} shown in Fig. 5 is similar to that observed in the scaling experiment (Fig. 3), suggesting that stimulus size is the main determinant of D_{max} as the scale is varied.

The above results were collected using the method of adjustment which is often used for the measurement of D_{max} (Aall, 1908 cited in Ogle, 1953; Ogle, 1953; Westheimer & Tanzman, 1956; Krekling, 1975; Schor & Wood, 1983). To rule out any possible influence of biases inherent in this method, we collected similar data using a staircase procedure in which crossed and uncrossed disparities were randomly interleaved within the same run. The starting disparity value for the two staircases was selected pseudo-randomly from a range of 3 times the standard deviation of the Gabor stimuli ± 1–5 pixels (a disparity beyond the fusion limit). The step size was held contant at 1 pixel; thus the step size in units of visual angle scaled with the viewing distance, ranging between 4.58 and 0.573 arc min for 0.5–4.0 m viewing distance.

On each trial subjects were instructed to first decide whether the central patch was in front of or behind the reference plane; if it was possible to make this judgment

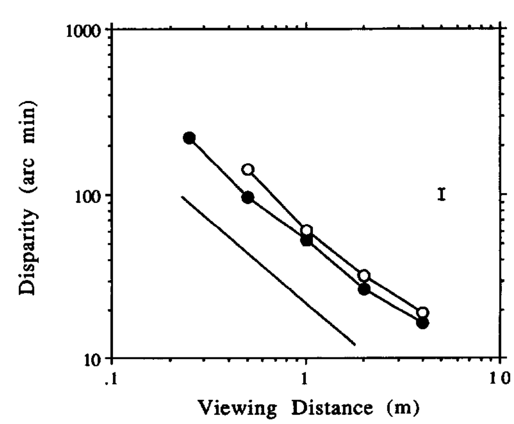

FIGURE 3. D_{max} is plotted here as a function of viewing distance, for two subjects JH (○) and LMW (●). Five viewing distances were used (0.25, 0.5, 1.0, 2.0 and 4.0 m) so that the carrier frequency of the stimuli ranged from 0.33 to 5.24 c/deg and the σ ranged from 91.6 to 5.73 arc min. Subject JH was not tested at 0.25 m. The slope values for the two functions are -1.0 (LMW) and -0.96 (JH). For comparison purposes, the solid line without symbols has a slope of -1 on these log–log axes. Error bars to the right indicate the maximum SEM for the data shown here.

*This downward trend is apparent in the data of JH with $\sigma = 22.9$ and 5.73 where the functions exhibit peaks at 0.5 and 1.31 c/deg respectively. Although in both instances these peaks are relatively large, they are not apparent in any of the other functions; we are not convinced that they reflect a genuine change in the sensitivity of the stereoscopic system. It is possible that these peaks are due to temporary changes in sensitivity that may have occurred because for this subject, in this condition, the test sessions took place over several different days. However, we have not validated this empirically.

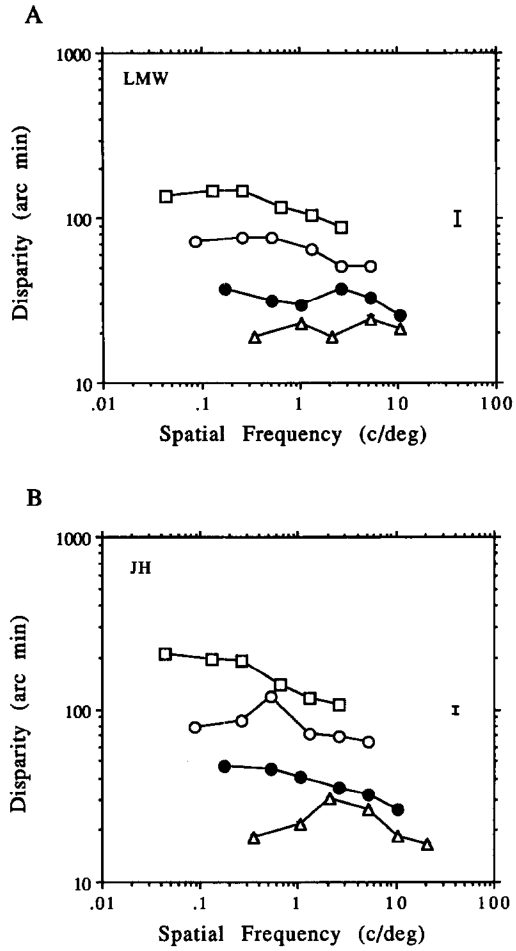

FIGURE 4. The effect on D_{max} of varying the carrier spatial frequency while holding the Gaussian envelope constant, is shown here for two subjects. These measurements were made for four envelope sizes: 45.8 (□), 22.9 (○), 11.45 (●) and 5.73 (△) arc min. The corresponding slope values are −0.12, −0.11, −0.05, −0.04 (LMW) and −0.13, −0.07, −0.14, −0.04 (JH) respectively. Error bars to the right indicate the maximum SEM for the data shown here.

they indicated that "yes", depth was visible. If it was impossible to judge the position of the target Gabor in depth, then subjects responded "no", depth was not present. Positive and negative responses resulted in increased and decreased disparity, respectively. Each staircase continued up to 41 reversals, the final D_{max} estimate was calculated by averaging all but the first reversal (40 estimates per point). The stimulus configuration was identical to that described in the methods section (shown in Fig. 1) as were the apparatus, test parameters, and subjects. As before, we recorded D_{max} as a function of the viewing distance, size, and spatial frequency of Gabor patches. The results are shown in Figs 6–8.

Comparison of Figs 3–5 with Figs 6–8 confirms that the results of the first experiment were replicated for both subjects in all conditions. The potential for individual differences in the processing of crossed and uncrossed disparities is exemplified in these data, where subject JH exhibits a consistent bias for crossed disparities, while LMW shows no such difference.

DISCUSSION

In all of the conditions tested here, the upper limit for stereopsis occurs after the stimulus is perceived as diplopic. For the majority of these conditions, the test stimuli are widely spaced; the distance between the two patches is several multiples of the period of the carrier. Under these conditions the stereoscopic system is forced to use the stimulus envelope to make a meaningful depth estimate.

Traditional theories of stereopsis, both computational and physiological, generally assume that stereoscopic processing involves an initial filtering stage followed by some binocular comparison procedure that extracts the disparity information (Marr & Poggio, 1979; Jones, 1991). The early filtering stage is often described in terms of the linear spatial frequency-tuned detectors, that are believed to form the substrate for monocular spatial vision (Campbell & Robson, 1968; Blakemore & Campbell, 1969; Watson & Robson, 1981). Experiments demonstrating the spatial frequency dependence of stereoacuity (Schor & Wood, 1983), and spatial frequency and orientation tuning functions for disparity mechanisms (Julesz & Miller, 1975; Mansfield & Parker,

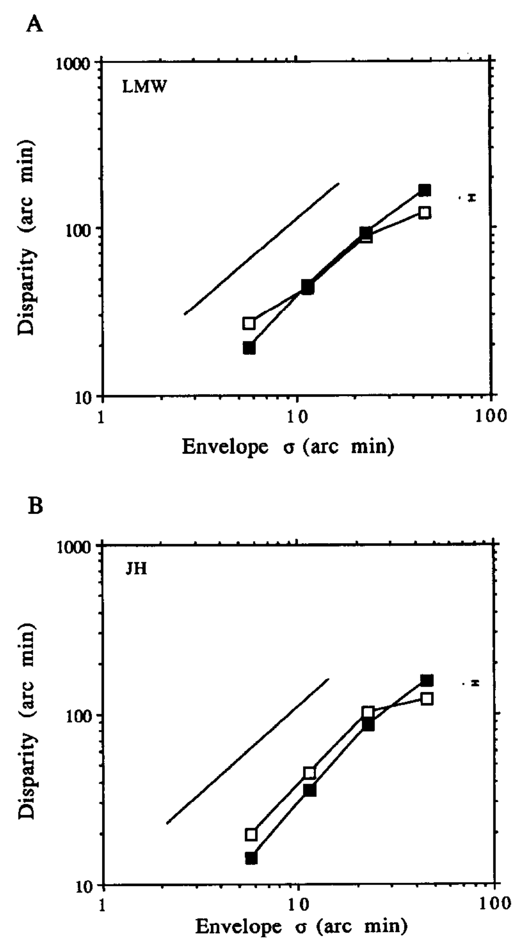

FIGURE 5. D_{max} is shown here as a function of envelope size, for two subjects. Envelope size ranged from $\sigma = 45.8$ to 5.73 arc min, and measurements were made for two carrier spatial frequencies, 1.31 (□) and 0.66 (■) c/deg. The slopes of the functions for each frequency are 0.76, 1.04 (LMW) and 0.91, 1.16 (JH). As in Fig. 3, the solid line shows a slope of 1 on log–log axes. Error bars to the right indicate the maximum SEM for the data shown here.

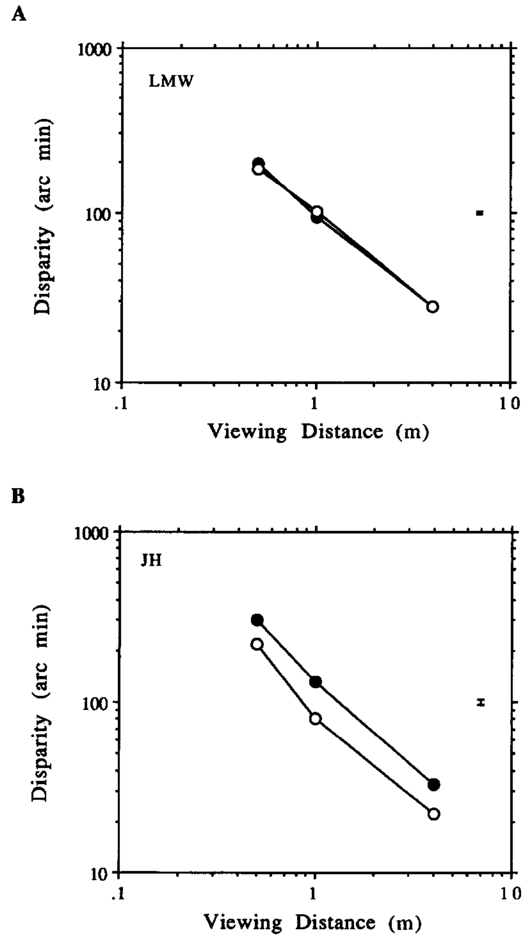

FIGURE 6. D_{max} is shown as a function of viewing distance, carrier spatial frequency, and envelope size for two subjects. Although a different psychophysical method was used (randomly interleaved staircase) the data were collected using the apparatus, display and subjects used to obtain results in Figs 3–5. Not all conditions represented in Figs 3–5 were tested. Variable viewing distance condition, 0.5, 1.0 and 4.0 m were tested. Each graph shows results for crossed (●) and uncrossed (○) disparities and the error bars indicate the maximum SEM for these data.

1993) support the contribution of these linear filtering operations to stereoacuity. However we argue that these filtering operations are not the only input to the binocular comparison stage. Instead we have provided evidence for the existence of a disparity signal that is supplied by the stimulus envelope (Hess & Wilcox, 1994; Wilcox & Hess, 1994). Since non-linear operations are required to extract the envelope disparity from the output of linear frequency-tuned filters we call this a *non-linear* disparity signal.

We believe that the non-linear operation identified in these D_{max} experiments also underlies the extraction of the envelope of spatially narrow band Gabor stimuli at small disparties and of interocularly uncorrelated noise patches (Wilcox & Hess, 1994). Our results suggest that when local spatial phase information is unreliable or unavailable the steroscopic system is able to exploit the coarse disparity signal provided by the contrast envelope of the stimulus. This capability might be very useful to the stereoscopic system, for example, in situations where relative depth judgements must be made between objects that are positioned off the horopter.

There are two alternative explanations for our results: one based on the role of vergence eye movements, and the other based on the influence of width judgments on assessments of D_{max}. Vergence eye movements could have influenced the results either by adding an extra source of variability, or by serving as a deliberate strategy to extend the range of stereopsis. We do not believe that vergence *errors* contributed to these results. If our stimulus arrangement was insufficient to allow stable, accurate convergence then we would expect random vergence errors to occur under all test conditions. These convergence fluctuations should be evident as high variability across test sessions. Since our standard error was on average only 0.05 arc min vergence errors are not likely to be a significant factor in our results.

It is possible that subjects altered their vergence as disparity was increased in an effort to reduce diplopia, and maintain the percept of depth at larger physical separations. However, the results displayed in Figs 6–8 argue against this. These data were obtained using an interleaved staircase procedure and replicate those obtained using the method of adjustment. Since crossed and uncrossed disparities were randomly interleaved it would have been impossible to adopt a vergence strategy to extend the fusion range. We conclude that the results do not reflect deliberate vergence strategies intended to reduce diplopia.

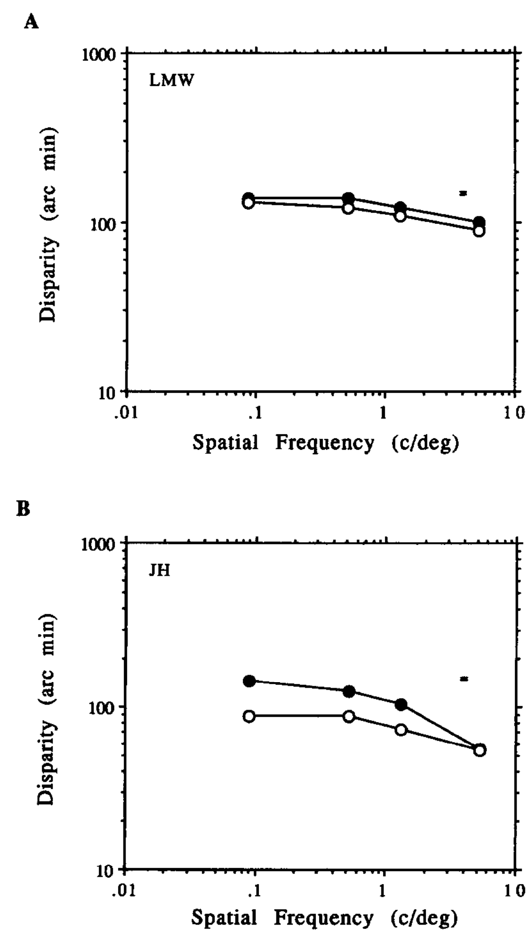

FIGURE 7. As in Fig. 6 here carrier frequency was varied for one envelope size (σ = 22.9 arc min).

Width judgments have been said to underlie *depth increment* tasks at large disparities (McKee, Levi & Bowne, 1990; Badcock & Schor, 1985). However, these are unlikely to have played a role in our estimates of D_{max} for the simple reason that in our experiments, there was no basis for making such width judgments. Because there was no comparison stimulus, subjects would have had to *arbitrarily* select a diplopic separation that they felt was appropriate to serve as the upper limit for stereopsis. And, they would have had to maintain this internal reference over several test sessions. If it were true that D_{max} was an arbitrary width chosen by each subject, then we would expect to obtain high variability across sessions and/or test conditions. At the very least, we would expect a between-subject comparison to reveal inconsistencies resulting from the arbitrary choice of D_{max}. The D_{max} results obtained using both psychophysical methods show that this is definitely not the case. Finally, both subjects reported that their decisions were based solely on the presence or absence of depth in the display.

Contrast

In light of the existing stereoacuity literature, which shows a strong dependence of stereoacuity on stimulus contrast, we were surprised to find no such dependence for D_{max} (Fig. 2). This suggests that the mechanisms that encode small and large disparities differ in more than just their spatial frequency tuning (Ohzawa *et al.*, 1990).

Previous research

In the experiments of Schor and Wood (1983) the upper limits for stereopsis were also measured using band-limited difference of Gaussian (doG) stimuli, at a range of stimulus sizes and spatial frequencies. The important difference between their work, and the experiments described here, is that we were able to separately vary the envelope size and carrier spatial frequency of our stimuli. Thus we were able to examine the separate roles of spatial frequency content and size in determining D_{max}. Since size and frequency content covaried in their study direct comparison of the experiments is difficult, however, we can make a crude comparison based simply on stimulus width. Both studies observe a dependence of the upper disparity limit on stimulus size over a similar range (between 5.73 and 45.8 arc min). However, Schor and Wood (1983) reported that this relationship followed a slope of 0.5 whereas we report a slope of 1. Analysis of the results of Richards and Kaye (1974) shows that there is a linear relationship between bar width and D_{max} (where perceived depth = zero) over most of the range investigated. The reason for the shallow slopes reported by Schor and Wood (1983) is not clear. Since we found no effect of contrast on D_{max}, we are confident that the difference is not due to a difference in contrasts [Schor & Wood (1983) used a constant high Michelson contrast of 100%].

A

B

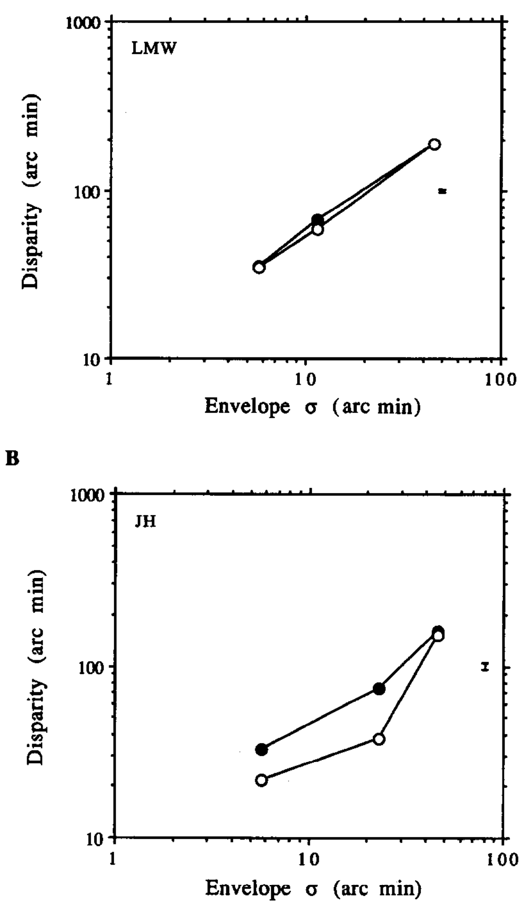

FIGURE 8. As in Fig. 6 here envelope sizes of 5.73, 11.45 and 45.8 arc-min were tested.

Another difference between our experiments and those of Schor and Wood (1983) is the variation in the distance between the centre of the stereo-target and reference elements with changing target size. Schor and Wood (1983) held the target to reference separation distance constant at 1.5 deg whereas in our experiments this distance scaled with target size (separation was 1.5 deg at 1 m). This difference might be important if D_{max} was limited by the frequency of the vertical depth modulation between the reference and target stimuli. Tyler (1973) has reported a linear relationship between the spatial frequency of the depth modulation and the upper disparity limit (termed disparity gradient limit). To assess the role of depth modulation in the experiments reported here, we measured D_{max} as a function of envelope size while maintaining a fixed *angular* inter-element separation. Results for two angular separations (1.5 and 2.3 deg) are depicted in Fig. 9 for crossed and uncrossed disparities for two subjects. These data show a strong dependence of D_{max} on target size for both separations and for crossed and uncrossed disparities. Note that at envelope sizes of 5.7 and 11.5 arc min, where both separations were tested, D_{max} is relatively* independent of the separation difference. These data show that D_{max} is determined primarily by the stimulus size and not

*We note there is a slight reduction of the slopes of the functions shown in Fig. 9(A, B). It is possible that at the two extreme separations used in our main experiments (3.0 and 0.38 deg) there might have been some small effect of separation that increased the overall slope of the functions.

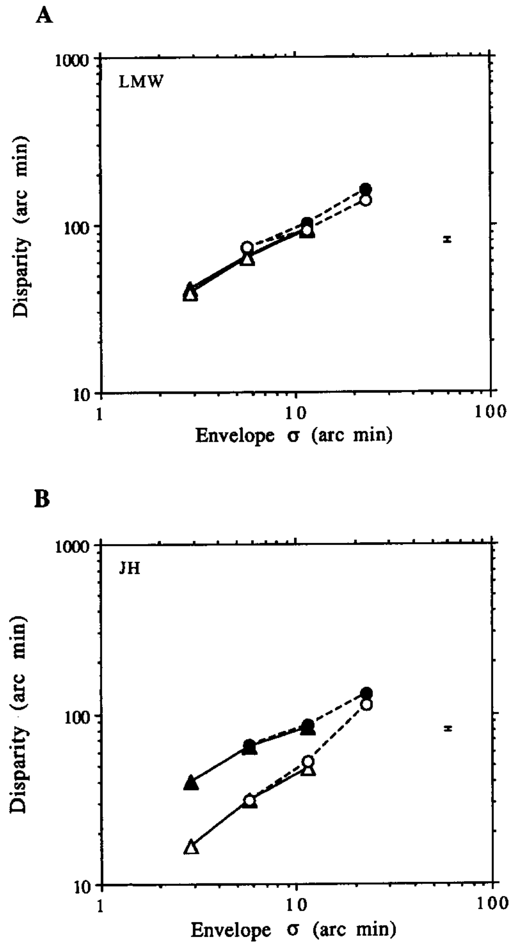

FIGURE 9. The staircase procedure used to produce the results displayed in Figs 6–8 was also employed to determine the effects of angular inter-target separation on D_{max}. Shown here are data for two subjects for two separations (1.5—triangles and 2.3—circles) for uncrossed and crossed disparities (open and solid symbols respectively). Error bars to the right indicate the maximum SEM for the data shown here.

by the separation between the reference and target patches.

Schor and Wood (1983) argue that their results illustrate the spatial frequency dependence of the upper limits of stereopsis, we have demonstrated that this is not the case. However, the majority of their data is consistent with our proposal that stimulus size is the limiting feature for D_{max} since spatial frequency and size covaried in their experiments. In a control condition which they cite as further evidence that spatial frequency tuned channels mediate the upper disparity limit, Schor and Wood (1983) measure D_{max} using *bars* of varying widths. They found that the results obtained using bars were the same as those obtained with doG stimuli. While Schor and Wood (1983) attribute this similarity to shared low frequency components, our results suggest that it is the size, not the spatial frequency similarity, of their stimuli which contributes to the similar values of D_{max}.

Fine vs coarse stereopsis

Ogle (1953) and Richards and Kaye (1974) observed that there is no dramatic change in stereosensitivity in the transition from fused to diplopic images. This result is the basis for Richards and Kaye's (1974) suggestion that the distinction between fine and coarse stereopsis simply reflects a change in the disparity tested; there are no differences in the way that the two classes of disparity are processed. Our data show that there is a common type of processing (non-linear envelope extraction) at large and small disparities. However, the relative unimportance of the fine structure, or carrier spatial frequency, in determining D_{max} suggests an important difference between fine and coarse stereopsis that has not previously been identified.

Although previous studies of coarse stereopsis have not searched for evidence of linear vs non-linear operations, there is indirect support for non-linear processing at large disparities. Ramachandran, Madhusudhan Rao and Vidyasagar (1973) created texture stereograms in which the disparate region was defined by uncorrelated random noise of a different scale than the noise in the surround. In spite of the absence of any local correlation in the two eyes, depth identification accuracy was at least 95% (although they do note that the quality of this percept was poor). Further, both Mitchell (1969), and Kaye (1978) reported that a measurable sensation of depth is obtained at large disparities using dichoptic patterns. In Mitchell's study horizontal lines were presented to one eye and vertical lines to the other, while in Kaye's experiment circles and crosses were similarly combined. In spite of the differences in the patterns viewed by the two eyes subjects were able to make reliable depth judgments. Note that in both of these experiments, although the local contour information was different, the overall size of the dichoptic stimuli was the same. It is possible that under these dichoptic viewing conditions the coarse stereoscopic system was unable to use local contrast variation and instead the contrast energy of the envelope of the pattern was extracted and used to assess relative depth.

Relevance to neurophysiology

According to the neurophysiologically-based model of disparity processing advanced by Ohzawa *et al.* (1990), large disparities are processed by linear operations of cells tuned to low spatial frequencies. On the other hand, the results of Ferster (1981) in cat and Poggio and Fischer (1977) in monkey suggest that there are neurones tuned to large disparities by means of a strong, non-linear inhibitory interaction from the non-dominant eye. This interaction can be modeled as an inhibitory input from a spatially displaced complex-cell (Dobbins, 1992). In Dobbins' description, the cell's disparity tuning is decoupled from its spatial frequency tuning. The results of our psychophysical manipulations of contrast and Gabor envelope size support the argument for the decoupling of spatial frequency and disparity at the upper limits of stereopsis.

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