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Differential binocular input and local stereopsis

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Abstract

Using fractal noise images, we measured the dependence of Dmin and Dmax for stereo on the interocular differences of spatial frequency and contrast. Dmin exhibits a strong dependence on the highest spatial frequency contained in the image, while Dmax exhibits a weaker dependence on the lowest spatial frequency contained within the image. Neither relationship was found to be different when the filtering was restricted to only one eye's image, although the effect of differential lowpass filtering for Dmin was greater than that of binocular lowpass filtering. Contrast is thought to affect stereo performance particularly when it is reduced in only one eye's image. We show that, at least for broadband fractal images representative of everyday natural images, interocular contrast differences are no more disruptive than binocular ones. These results bear upon the nature of the matching process in stereopsis. The fact that these interocular spatial frequency and contrast manipulations do not selectively degrade stereopsis beyond that expected from a consideration of purely monocular effects is consistent with matching occurring within multiple spatial channels prior to their combination.

Keywords: Interocular spatial frequency; Interocular contrast; Filtering; Stereopsis; Matching

1. Introduction

The early stages of visual processing are composed of neurones with bandpass spatial filtering properties (Blakemore & Campbell, 1969; DeValois & DeValois, 1988). A number of studies utilizing different approaches have shown that these spatial channels are present at the site where stereo information is processed (Blakemore & Hague, 1972; Felton, Richards, & Smith, 1972; Julesz & Miller, 1975; Mayhew & Frisby, 1976, 1978; Prince, Eagle, & Rogers, 1998).

The relationship between these early channels and stereo processing is still controversial. For example, some investigators believe that the information from these early spatial filters is combined for the computation of image primitives prior to stereo matching. Support for this comes from studies showing the importance of element density (Glennerster, 1998), from a number of course-to-fine models of stereopsis (Nishihara, 1984; Quam, 1987; Schor & Heckmann, 1989; Watt, 1987) and from reports of interactions between widely separated spatial frequencies in stereopsis (Mayhew & Frisby, 1978).

The opposing view is that matching occurs within individual spatial frequency channels each with its own disparity limit. This is supported by a number of psychophysical studies (Heckmann & Schor, 1989; Julesz & Miller, 1975) and by neurophysiological data (Ohzawa, DeAngelis, & Freeman, 1990, 1996; Ohzawa & Freeman, 1986). More recently, Hess, Liu, and Wang (2002) have shown that, for binocularly filtered 2-d fractal noise images, Dmin (defined as the minimum detectable disparity) is affected in a way that suggests stereo is computed within rather than across spatial channels. The results for the measure Dmax (defined as the maximum detectable disparity) appear not to follow this simple rule.

To understand better the nature of the matching that occurs in stereopsis we measured both Dmin and Dmax for disks composed of broadband fractal 2-d noise. We use fractal noise to optimally stimulate spatial channels of similar octave bandwidths (Field, 1987). The noise

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was subjected to both lowpass and highpass filtering which was applied to either both eyes' images equally or to just one eye's image. One simple prediction that comes from the hypothesis that information is matched at the level of individual spatial channels is that binocular and monocular spatial filtering should be equally disruptive. On the other hand, if matching is between spatial primitives that are derived by channel combination (i.e., combination across scale) then filtering that differs between the eyes would be more disruptive. Consider the stimulus examples shown in Fig. 1. In Fig. 1B and C two sets of images are shown, in the first set, one of the images has been lowpass filtered (cutoff at 1 c/deg) in the second set, one of the images has been highpass filtered (cutoff at 1 c/deg). For any stereo model of binocular matching where correspondence is made between nearest neighbour features in the neural image, be they edges, zero-crossings or centroids, stereopsis would be severely degraded due to the number of false local matches between images so disparate in their local features as these. Using a quantitative model of nearest neighbour matching for motion processing, performance based on matching zero-crossings or centroids for images identical to that shown in Fig. 1B and C is at chance (Hess, Bex, Fredericksen, & Brady, 1998). On the other hand, for any stereo model based on the matching within individual spatial channels (assuming channel independence), such disparate images lead to only minor disruptions in performance. For example, in the lowpass case, Dmin would be increased due to a reduction in the highest *common* spatial scale and in the highpass case, Dmax would be reduced due to a reduction in the lowest *common* spatial scale. Such reductions would be no different if the spatial filtering was applied to one or both eyes' input (Hess et al., 1998). Thus a careful comparison of how performance is reduced for comparable monocular and binocular filtering conditions allows one to tease apart losses primarily due to filtering from those primarily due to the matching (i.e., where matching primitives require substantial cross-scale support).

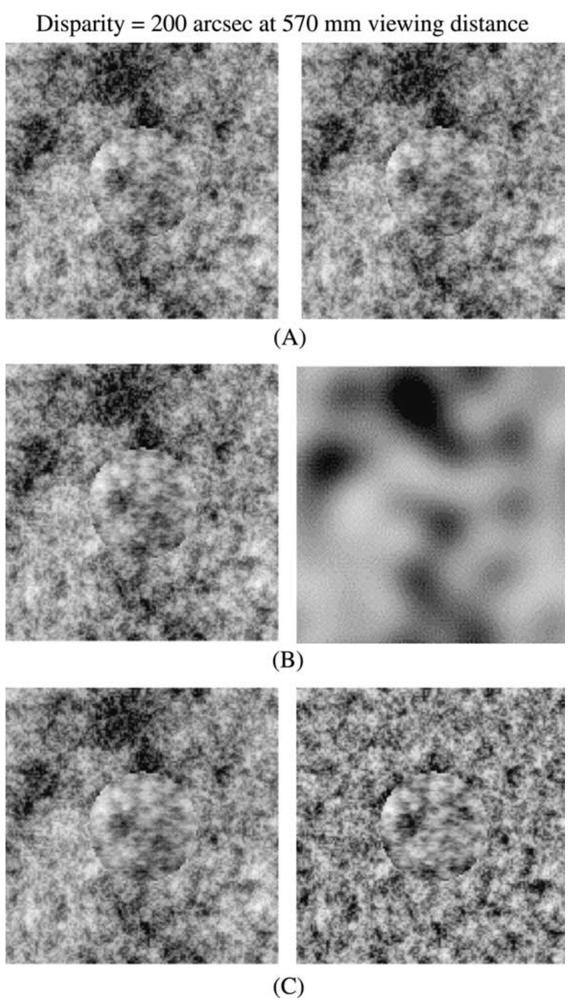

Fig. 1. Examples of stereo pairs used. In this example, fractal noise in only one of the image pairs was filtered. The horizontal disparity was introduced by shifting the fractal noise within a circular patch at the center of image. The central test disc had a radius of 1°, unless otherwise stated and the background noise field was fixed at 5° × 5°. The whole stimulus was presented in a square frame with upper and lower vernier fusion markers. (A) No filtering; (B) lowpass filtering (cutoff = 1 c/deg); (C) highpass filtering (cutoff = 1 c/deg).

A number of previous studies examined susceptibility of stereo acuity (Dmin) to spatial frequency and contrast imbalances in the two eye's inputs. However, no consensus has emerged for either of these image attributes. For example, some studies (Simons, 1984; Westheimer & McKee, 1980; Wood, 1983) argued that lowpass filtering, when applied to only one eye's image is particularly disruptive to stereopsis, while others (Julesz, 1971) argue that stereopsis is particularly resistant to monocular blur. Several studies also showed that the vulnerability of the stereo system to contrast imbalances in the two eye's images depends on spatial frequency. A greater vulnerability to interocular contrast difference occurs for low rather than high spatial frequencies (Cormack, Stevenson, & Landers, 1997; Halpern & Blake, 1989; Legge & Gu, 1989; Schor & Heckmann, 1989; Stevenson & Cormack, 2000).

Since this issue ultimately bears upon the nature of the stereo matching process and its relationship to the early spatially tuned detectors, we have set out to resolve it. We assess not only stereo acuity (Dmin) but also Dmax to get a comprehensive picture of stereo performance. We do this for not only lowpass filtering but also highpass filtering because the former is expected to influence the processing of small disparities and the latter is expected to influence large disparities. We use spatially broadband stimuli that are designed to provide comparable stimulation (i.e., fractal) of the full range of spatial detectors (Field, 1987) thought to operate at the early stages of human visual processing (Blakemore &

Campbell, 1969; Stromeyer & Julesz, 1972; Wilson & Bergen, 1979).

2. Methods

2.1. Stimuli

Stimuli were stereo images composed of spatially filtered or unfiltered fractal noise. Examples of unfiltered and filtered stereograms are shown in Fig. 1. The subject viewed these images with a stereoscope so that the left image was only seen by the left eye and the right image by the right eye. The viewing distance was 57 cm. Stimuli were generated digitally in MATLAB (MathWorks, Inc.) and displayed on a gamma-corrected, Macintosh gray-scale monitor (mean luminance 50 cd/m^2) using the Psychophysics Toolbox (Brainard, 1997) which provides high level access to the C-language VideoToolbox (Pelli, 1997).

Two-d fractal noise was generated by weighting the amplitude spectrum of the uniformly distributed noise by one over spatial frequency ($1/f$). Horizontal disparity was introduced by shifting the fractal noise contained within a circular patch at the center of each stereogram. Thus, the disparity is confined to the noise within a zero disparity aperture. The radius of the circular patch was 1°. Since the disparity was introduced after the generation of fractal noise, the edge of the patch was sometimes visible in stereo images. Ideal lowpass and highpass spatial filters (i.e., a rectangular profile filter that deleted frequency components outside the pass band) were used to generate filtered stereograms. Spatial filtering was carried out after the disparity and the stimulus windowing were introduced, so that the filtering process involved both the edge of the circular patch and the fractal noise contained within it. This ensured that unwanted frequency components were not introduced as a consequence of the disparity or window generation.

The method of sub-pixel displacement was used to achieve horizontal disparities of less than 10″ at the viewing distance of 57 cm. The sub-pixel shift was realized by a linear interpolation between a pattern and its one-pixel shifted version. The following formula was used to compute sub-pixel shift images.

$$\mathrm{Image}_{\mathrm{Sub}} = p \times \mathrm{Pattern}_{\mathrm{One\,Pixel}} + (1 - p) \times \mathrm{Pattern} \tag{1}$$

where p is the amount of sub-pixel shift ($0 < p < 1$). The image analysis in MATLAB indicated that, for a screen resolution of 2.7 pixels/mm and a viewing distance of 57 cm, the difference between left and right images was present for horizontal disparity as small as 1″. This method can reduce the contrast of high spatial frequency components and may not be suitable for all types of broadband images. For example, our fractal images in the high spatial frequency band (5–10 c/deg) suffered a 9.37% loss in energy for the disparity values used.

In additional to the difference in spatial frequency content, the total energy (or contrast) in a spatially filtered stereo image was also different from that in an unfiltered $1/f$ image. In all experiments but one (Fig. 4) we did not readjust the energy in the unfiltered bands. To determine the role of spatial frequency per se on stereo acuity (Fig. 4), we needed to equalize the total amount of energy in images before and after filtering. This was implemented as follows. First we computed root-mean-square (RMS) value of unfiltered image, *rms*. Then we computed RMS value of filtered image, *rms_flt*. Finally we multiplied the filtered image by the ratio of these two RMS values (*rms*/*rms_flt*). Table 1 gives the normalization ratios for different cutoff frequencies of lowpass filtering.

2.2. Procedure

A two-alternative, forced-choice (2AFC), constant stimuli paradigm was employed to estimate Dmin and Dmax. In a trial, a pair of stereo images was presented on the screen for 0.5 s. The circular patch at the center of the cyclopean image was either in front of the reference plane or behind it. The subjects' task was to identify the direction of the offset. Each run consisted of 10 trials for each of 10 disparities (five crossed and five uncrossed). Audio signals were used to prompt the subject just before and after each trial. No feedback about the correctness of responses was provided. Psychometric functions of correct responses versus disparity were generated, and a Weibull function (Weibull, 1951) was used as a closed-form analytic approximation to a cumulative normal to fit to the combined data. Embedding a noise test patch within a zero disparity, noise-surround produced minimal bias for crossed versus uncrossed disparity. We verified this by comparing the separate responses to crossed and uncrossed disparities.

2.3. Subjects

Two subjects (two of the authors) experienced at psychophysical experiments were tested. Both had normal acuity and no sign of ocular pathology.

Table 1
Normalization ratios for different cutoff frequencies of lowpass filtering

Cutoff (c/deg)	Ratio (unfiltered/filtered image)
20	1.00
15	1.005
10	1.045
5	1.145
2.5	1.262
1.25	1.450
0.625	1.750

In the first part of this study, we investigated the effect of differential low and highpass filtering on Dmin and Dmax. In the second part of the study, we investigated the effect of differences of interocular contrast on Dmin and Dmax for filtered and unfiltered stereograms.

3. Results

3.1. The effect of differential spatial filtering on Dmin and Dmax

The effects of differentially filtering the spatial information from just one eye's image is shown in Fig. 2 for two subjects. Here the stereo measure is Dmin and the effects of both lowpass (upper two frames) and highpass (lower two frames) filtering are assessed. The results are plotted in terms of the highest (lowpass filtering) and lowest (highpass filtering) cutoff frequency of the ideal filter applied to only one eye's image. The other eye's image was unfiltered. Dmin shows a rapid deterioration when one eye's image is lowpass filtered for both stimulus conditions (symbols). However, Dmin is unaltered when one eye's image is highpass filtered. Furthermore, the dependence on lowpass filtering (symbols in the two upper frames) is stronger in the case of uniocular filtering compared with comparable binocular filtering (solid curve). For example, when the uniocular filter cutoff is at 2 c/deg, the elevation for Dmin for RFH was a factor of 30 and for CLH, a factor of 15 more than that found for the binocular case. These binocular results were derived from a previous study using identical stimulus conditions except that the filtering was applied equally to both eye's images (Hess et al., 2002).

Comparable results for the stereo measure Dmax are shown in Fig. 3. Again stereo performance (symbols) is compared for both lowpass (two upper frames) and highpass (lower two frames) filtering. These results are compared with previous results where we used identical stimulus conditions except that the filtering in this case was applied equally to both eyes' images (solid curve). The results indicate that Dmax is not greatly affected by lowpass filtering of one eye's image (two upper frames) because the thresholds are not significantly different ($p > 0.05$: one-tailed paired t-test). However, there is a loss of performance when one eye's image is highpass filtered (two lower frames). Here the thresholds for the unfiltered and extreme highpass conditions are significantly different ($p < 0.05$: one-tailed paired t-test). Comparable filtering applied binocularly (solid curve is

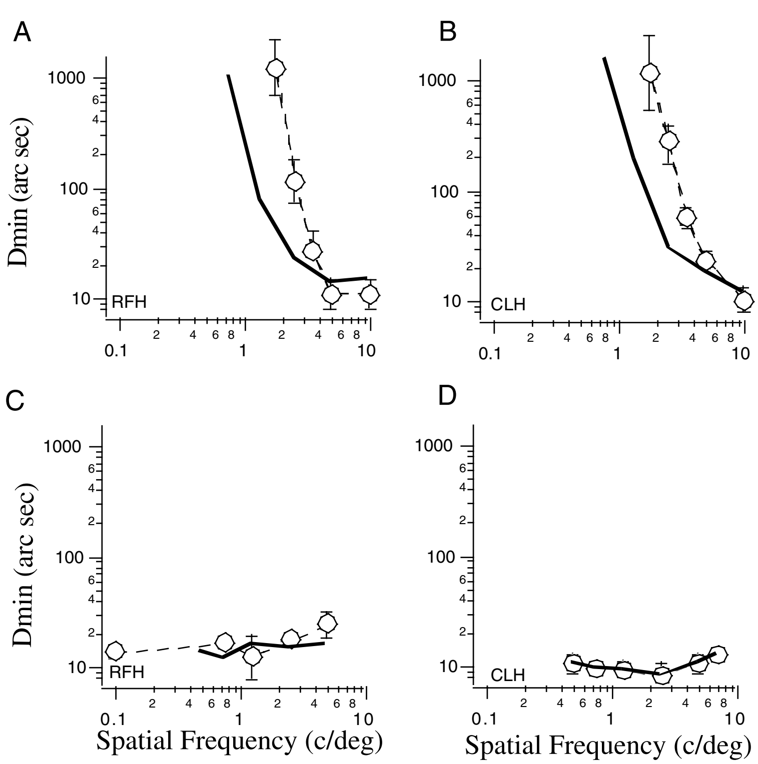

Fig. 2. The effect of lowpass (A and B) and highpass (C and D) filtering of one eye's image on Dmin. The stimulus is a patch of fractal noise and the disparity is confined to the noise (open symbols) within the central patch. For lowpass filtering, the results are plotted against the high cutoff of the ideal filter. For highpass filtering, the results are plotted against the low frequency cutoff of the ideal filter. Lowpass filtering affects Dmin, highpass filtering does not. The solid curve is the average result for these two conditions from a previous study (Hess et al., 2002) when the filtering is applied to both eyes' images equally. Error bars represent ±1 sd.

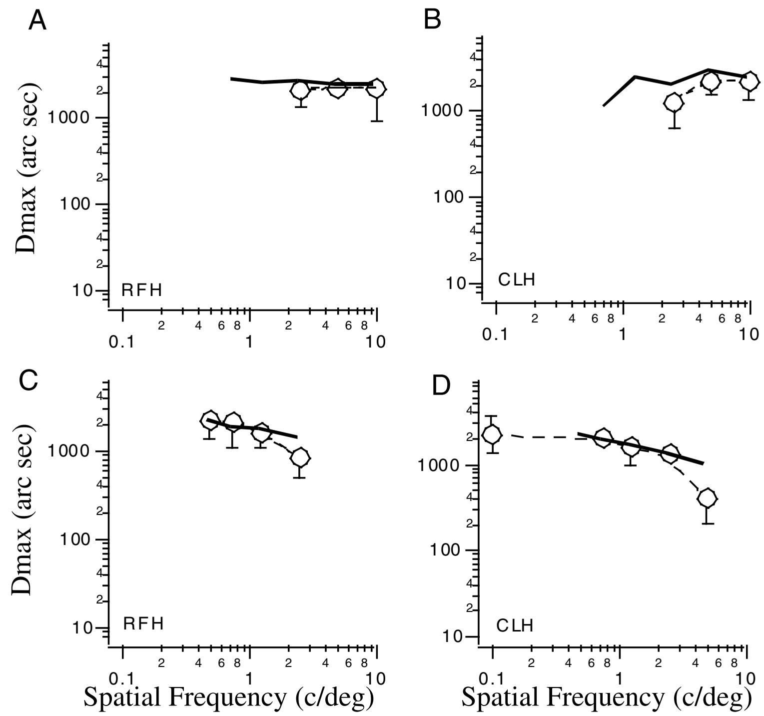

Fig. 3. The effect of lowpass (A and B) and highpass (C and D) filtering of one eye's image on Dmax. The stimulus is a patch of fractal noise and the disparity is confined to the noise contained within the central patch (open symbols). For lowpass filtering, the results are plotted against the high cutoff of the ideal filter. For highpass filtering, the results are plotted against the low frequency cutoff of the ideal filter. Highpass filtering affects Dmax more than lowpass filtering. The solid curve is the average result for these two conditions from a previous study (Hess et al., 2002) when the filtering is applied to both eyes' images equally. Error bars represent −1 sd.

the average result for the two comparable stimulus conditions from Hess et al., 2002) show similar results (thresholds not statistically difference at $p = 0.05$: one-tailed paired t-test).

The clearest case where stereo performance is selectively compromised by monocular as compared with binocular filtering is in the case of lowpass filtering for the measure Dmin. The greater loss of stereo acuity in the case of uniocular as compared with binocular lowpass filtering could be due to a number of reasons. When one eye's image is spatially filtered, not only is the extent of the spectrum reduced but also the overall contrast energy is reduced in the filtered image. This was the case for the results shown in Fig. 2. The greater influence of uniocular lowpass filtering in this case may be due to the imbalance (in the non-overlapping part of the spectrum) in the overall contrast energy that occurs between the filtered and unfiltered eyes' images. To test this we remeasured the effects of uniocular lowpass filtering but this time equating the overall energy of the filtered and unfiltered images. In all other experiments we simply filtered the fractal image without altering the contrast of the unfiltered components. Now we adjust the contrast of the unfiltered components so that, for all lowpass filtering conditions, the overall contrast energy in the filtered and unfiltered images are equated. These results are shown in Fig. 4 (filled symbols for the equal energy case of differential lowpass filtering) and compared with the previous results (Fig. 2A and B—unfilled symbols) where the differential lowpass filtering was not equated for energy (unfilled symbols and dashed curve). The greater falloff in Dmin performance with uniocular lowpass filtering (two upper frames of Fig. 2) is not due to any difference in the overall energy of the filtered and unfiltered images. This follows from the finding that equating for contrast energy between the filtered and unfiltered eyes' images does not affect the rate at which Dmin falls off with differential lowpass filtering. These data are represented by filled and unfilled symbols and are not significantly different ($p > 0.05$: one-tailed paired t-test).

Another possibility for the lower performance in the uniocular case is that the extraneous high spatial frequency noise that is present in the unfiltered eye's image necessitates the use of a lower spatial frequency filter to achieve the same Dmin signal/noise ratio. This is shown schematically in Fig. 5 where there is a diagrammatic representation of the three highest frequency filters utilized by the stereo system together with overlaid stimulus lowpass filtering functions (thick lines). These filtering functions are one of two types, linear or stochastic. In the linear case, the vertical thick lines indicate the frequencies above which the amplitudes of the components are set to zero, whereas in the stochastic

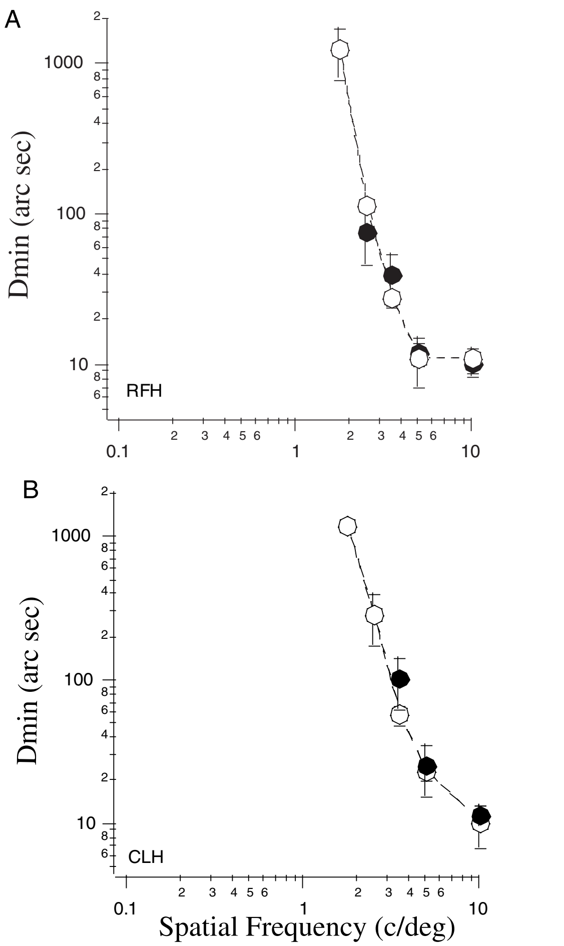

Fig. 4. A comparison of lowpass filtering of one eye's image for images equated in overall contrast energy. The disparity was confined to the noise within the central stimulus patch. In the case depicted by the unfilled symbols, the contrast of the unfiltered components in the image were unaltered as was also the case for the results shown in Fig. 2A and B. However, in the case depicted by the filled symbols, the overall energy of the filtered and unfiltered images was kept constant. The maximum contrast was set to 0.45. The falloff with filter cutoff is a primary spatial frequency and not a secondary contrast energy effect. Error bars represent ±1 sd.

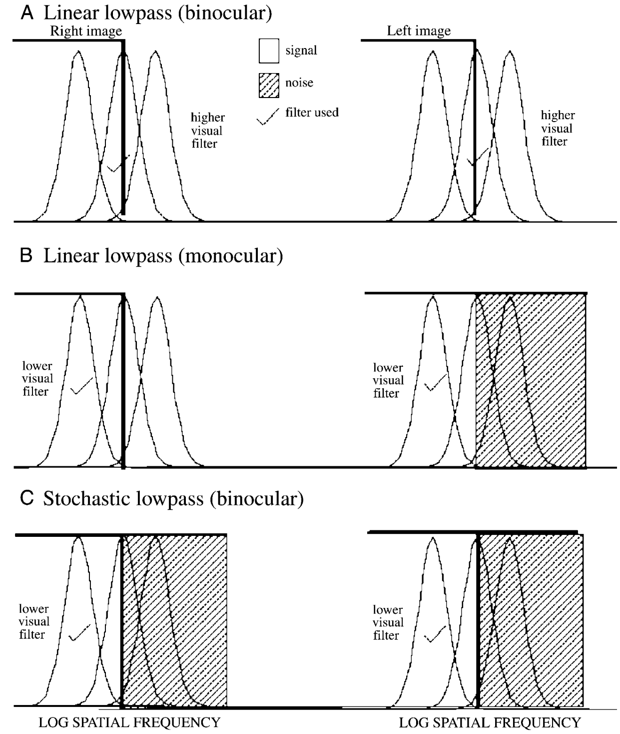

Fig. 5. Schematic representation of the relationship between a spatial filter's peak position and the cutoff of the lowpass filter in the current stereo experiments. The thick vertical lines represent the filter cutoff. For the linear filter, this indicates where amplitude components are set to zero whereas in the case of the stochastic filter, it represents where phase values are scrambled (diagonal hatching). The thin vertical line in the right frame of B represents the lower bound of frequencies that are present in the unfiltered image of one eye but not in the filtered image seen by the other eye. Two cases of linear (amplitudes beyond the cutoff set to zero) spatial frequency filtering are depicted, one binocular (A), the other uniocular (B). One case of stochastic (amplitudes beyond cutoff unaltered but their phases are scrambled) filtering is depicted (C). Because of correspondence/disparity noise (i.e., uncorrelated/random disparity signals), a lower spatial frequency filter must be used in the case of either monocular, linear (B) or binocular, stochastic filtering (C) compared with binocular, linear filtering (A).

case, they indicate the frequencies above which the phases of the components are randomized. In the case where the filtering is binocular (Fig. 5A), to achieve a criterion signal to noise ratio, the visual system can utilize a spatial filter at or exceeding the image's filter cutoff, whereas in the case of a uniocularly filtered image, a lower spatial frequency mechanism would need to be used (Fig. 5B). Quantitative predictions have been derived in the comparable case for motion in which differential spatial filtering is applied to different frames (as opposed to different eyes) in a two-frame motion (as opposed to stereo) sequence (Hess et al., 1998, their Fig. 6). A simple test of this explanation is that results similar to that for uniocular lowpass filtering should be obtained when binocular stochastic filtering is used (Fig. 5C) because in this case, even though the filtering is binocular, there is a similar signal/noise argument for utilizing a lower (than in the case of binocular linear filtering; Fig. 5A) spatially tuned mechanism.

In Fig. 6, results are compared for uniocular linear, lowpass filtering (e.g. two upper frames of Fig. 2) and for binocular stochastic filtering in which the phase randomization is binocularly uncorrelated (Fig. 5C). The uniocular, linear filtering results for the two standard stimulus conditions are shown as unfilled circles whereas the binocular stochastic filtering results are shown as unfilled squares. The good correspondence between these two results suggests that the more disruptive effect of lowpass filtering in the uniocular case could be the result of an interference effect at the site of stereoscopic processing owing to the presence of extraneous high frequencies in the unfiltered eye's image. Subsequent experiments showed similar results (Table 2)

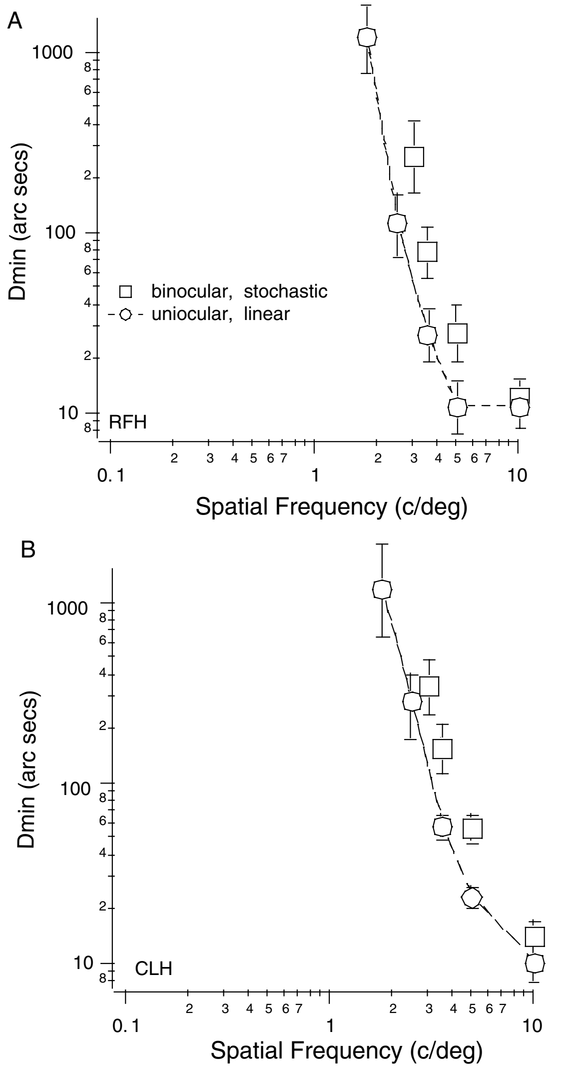

Fig. 6. The effects of linear lowpass filtering one eye's image on Dmin (circles) compared to that of binocular stochastic (squares) filtering. The disparity was confined to the noise within the central stimulus patch. Qualitatively similar results (the small difference that remains for the stochastic filtering results is statistically significant) are obtained for these two types of filtering though one is monocular and the other, binocular, for reasons schematically illustrated in Fig. 5. Error bars represent ±1 sd.

to those described above (unfilled squares in Fig. 6) for monocular stochastic filtering and for binocular stochastic filtering where the phase scrambling was correlated between the two eyes' images. Stereopsis is disrupted to the same extent regardless of whether the extraneous frequency components are themselves interocularly matched. There remains a small (Dmin thresholds are on average 50–80% higher for binocular stochastic filtering than for monocular linear filtering) but significant ($p < 0.05$: one-tailed paired t-test) difference between the results obtained by monocular and binocular filtering. We interpret the correspondence between correlated and uncorrelated versions of stochastic filtering to suggest that performance is being

Table 2
Comparison of thresholds for monocular (linear versus stochastic) and binocular (correlated versus uncorrelated) filtering

Lowpass filter cutoff (c/deg)	Linear monocular filtering	Stochastic monocular filtering
Monocular lowpass filtering		
10.0	12.2 (±2.4)	10.3 (±3.0)
5.0	23.6 (±4.2)	25.5 (±4.4)
3.5	45.9 (±7.1)	42.3 (±8.8)
2.5	270.1 (±48.6)	301.2 (±45.2)
	Uncorrelated	Correlated
Binocular stochastic lowpass filtering		
10.0	9.6 (±2.1)	10.5 (±2.2)
5.0	24.4 (±4.8)	26.1 (±4.0)
3.5	60.1 (±8.8)	55.7 (±10.2)
2.5	334.7 (±43.1)	386.3 (±52.1)

limited by disparity noise introduced by the phase scrambled components.

3.2. The effect of interocular differences of contrast on Dmin and Dmax

Previous studies (Halpern & Blake, 1989; Legge & Gu, 1989) have highlighted the importance of relative contrast information in the two eye's images for stereo. These studies have shown that for narrowband spatial targets (i.e., sinusoids or DOGs) reducing the contrast in one eye's image is more disruptive than the same reduction in both eyes' images. However, more recently, Cormack et al. (1997) using a spatially broadband stimulus (e.g., dynamic spatial noise) showed that noise images of unequal contrast had little effect on stereo acuity and suggested that this was due to the presence of higher spatial frequency components in the image. Support for this view was later provided in a study using spatially narrow band stimuli (Stevenson & Cormack, 2000).

To ascertain the importance of uniocular contrast differences for stereo performance for the types of images representative of everyday scenes (e.g., fractal images) we assessed the influence of uniocular (filled symbols) as well as binocular (unfilled symbols) changes in the maximum contrast of our fractal noise images. We made this comparison for the measures Dmin and Dmax for unfiltered, lowpass filtered and highpass filtered stimuli. These results for two observers are displayed in Fig. 7 for Dmin and Fig. 8 for Dmax. Dmin (Fig. 7) exhibits only a weak dependence on contrast consistent with the established square root relationship (the mean slope on these log/log coordinates for the uniocular data was 0.485 (±0.17), whereas that for the binocular data as a whole the mean slope was 0.732 (±0.16). This is within the range of previous reports (Halpern & Blake, 1989; Legge & Gu, 1989). Apart from

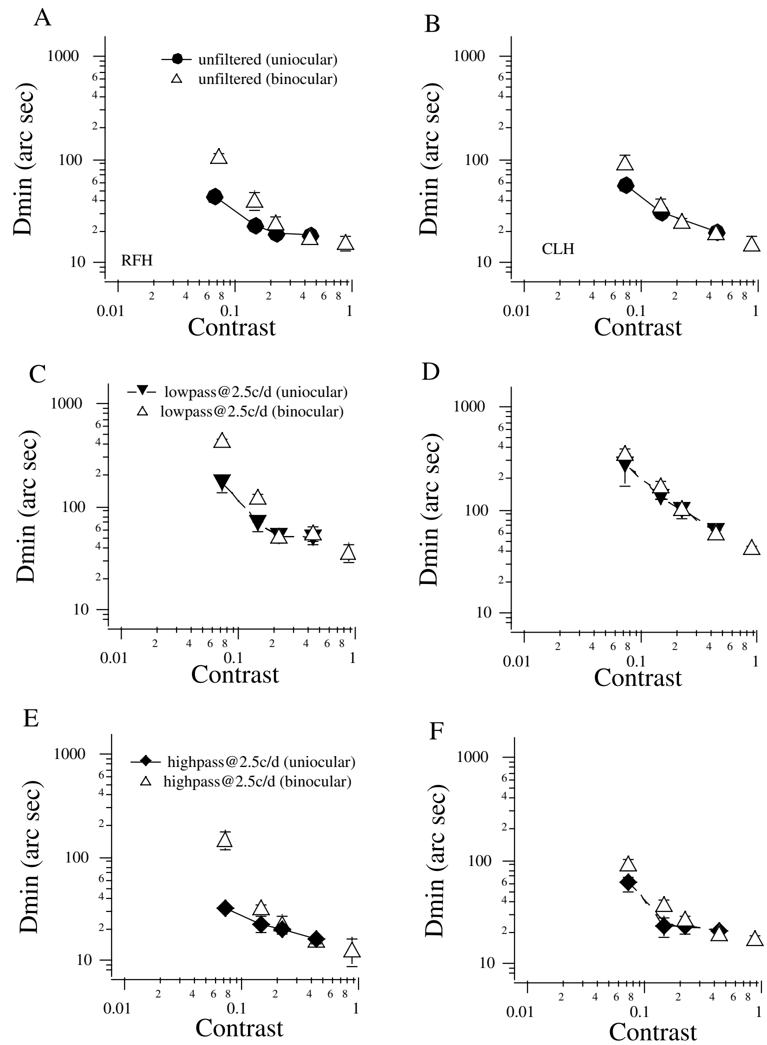

Fig. 7. The effect of contrast on Dmin for stereo. Uniocular (filled symbols) and binocular (unfilled symbols) contrast changes are compared for filtered (lowpass or highpass) or unfiltered fractal noise images. Monocular contrast changes do not result in worse stereo performance than comparable binocular changes. Error bars represent ±1 sd. For monocular contrast changes, the contrast of one eye's image was fixed at 0.9 and the contrast of the other eye's image was varied as indicated on the horizontal contrast axis.

the data at the lowest contrasts (particularly that of RFH), similar reductions in stereo performance are seen for contrast changes whether they are binocular or uniocular. At the lowest contrast the results suggest a greater loss of performance for binocular compared with uniocular reductions in contrast. The finding that binocular and uniocular contrast reduction results in a similar loss of stereo acuity is true for targets of all spatial composition (unfiltered, lowpass filtered and highpass filtered).

In Fig. 8, comparable results are displayed for the stereo measure Dmax. The effect of binocular changes in contrast are small and exhibit a shallower than square root relationship. The mean slope on these log/log coordinates for the monocular data was 0.325 (±0.09), whereas that for the binocular data was 0.335 (±0.11). Uniocular contrast reduction produces comparable loss of performance to that for binocular contrast reductions for all spatial targets (unfiltered, lowpass filtered, highpass filtered). Contrary to the well established view from studies using narrowband spatial targets (Halpern & Blake, 1989; Legge & Gu, 1989; Schor & Heckmann, 1989; Stevenson & Cormack, 2000), the current results support the previous findings of Cormack et al. (1997) who found that uniocular reductions in contrast are no more disruptive than binocular contrast reductions for broadband images. However, our use of spatial filtering is not consistent with the proposal put forward by Cormack et al. (1997) that this effects is a consequence of the high spatial frequency content of images. We show that it is the case for images with only high spatial frequencies (highpass filtered images) and images with only low spatial frequencies (lowpass filtered images).

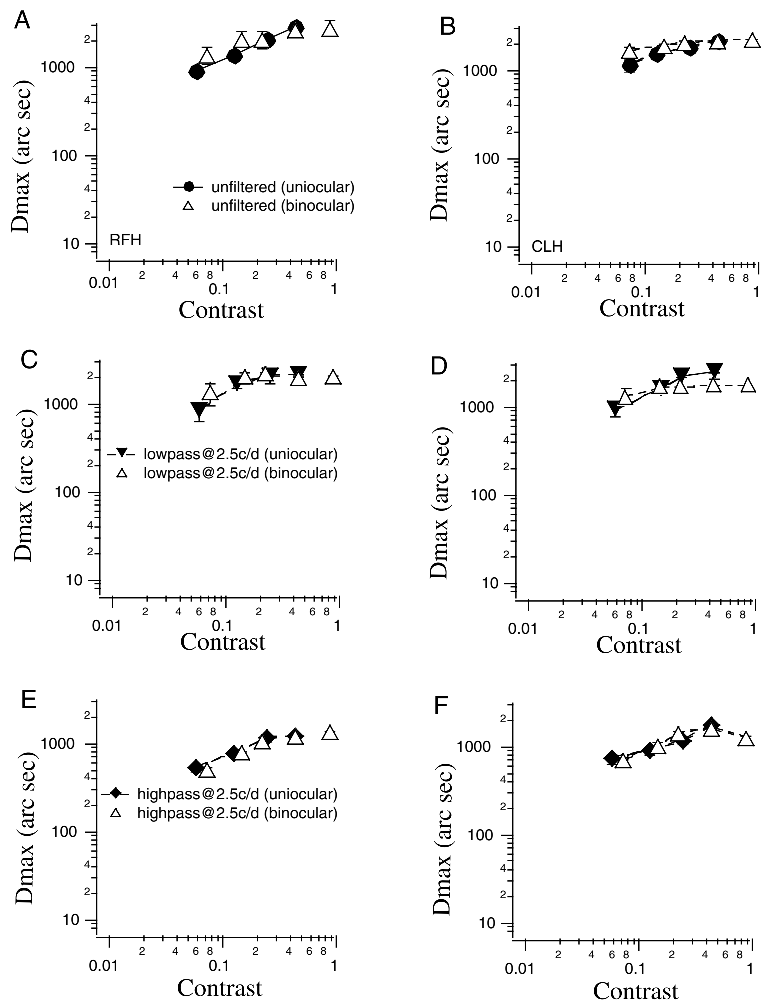

Fig. 8. The effect of contrast on Dmax for stereo. Uniocular (filled symbols) and binocular (unfilled symbols) contrast changes are compared for filtered (lowpass or highpass) or unfiltered fractal noise images. Monocular contrast changes do not result in worse stereo performance than comparable binocular changes. Error bars represent ±1 sd. For monocular contrast changes, the contrast of one eye's image was fixed at 0.9 and the contrast of the other eye's image was varied as indicated on the horizontal contrast axis.

4. Discussion

The present study examined the issue of how similar the retinal images of the two eyes need to be to support good stereo performance. This is an unresolved issue that bears upon the nature of the matching process. In particular, we considered two parameters, spatial frequency and contrast and compared performance for binocular (equal variation to each eye's image) versus monocular (interocular variation to one eye's image only) manipulations. Our reasoning was that any differential loss of performance for a parameter varied interocularly would highlight its potential importance in the correspondence process. Our results which suggest that the stereo system is differentially sensitive to interocular differences in spatial frequency but not to interocular differences in contrast, help to resolve previous contradictory reports on the subject.

4.1. Spatial frequency

In the first part of this study we reported that it is the differential high frequency composition of the two eye's images that most affects stereo performance, though this is limited to stereo acuity (Dmin). Dmin is elevated by more than an order of magnitude when one eye's image is differentially lowpass filtered. For example, when the cutoff of the lowpass filter was at 2 c/deg, the average elevation of Dmin for our two subjects was a factor of 22 (Fig. 2). A similarly strong dependence on the differential low spatial frequency composition of left and right eye images was not observed for Dmax. This reduction in stereo acuity when only one eye's image is lowpass filtered has been reported by a number of previous investigators (Simons, 1984; Westheimer & McKee, 1980; Wood, 1983). At first glance this finding that monocular lowpass filtering is more disruptive than the equivalent binocular lowpass filtering seems to be contrary to the suggestion that stereo matching occurs within a number of independent spatially tuned disparity detectors (Julesz, 1971; Julesz & Miller, 1975). However we feel that this finding can be reconciled with the notion of matching/stereo processing occurring within separate spatially tuned stereo detectors by considering the noise introduced at the matching/stereo processing stage (for an independent spatially tuned detector) by the extraneous higher spatial frequencies present in the unfiltered image (see Fig. 5). Assuming that matching/stereo processing does occur within independent spatially tuned mechanisms, then on signal/noise grounds alone, one would expect that a spatially tuned mechanism of a lower peak frequency (assuming independent spatially tuned stereo detectors) would have to be used in the case of interocular filtering compared with its binocular counterpart (see Fig. 5). Such a shift in the spatial scale of analysis would result in a lateral displacement of the Dmin versus filter cutoff frequency function for interocular filtering along the abscissa to the left (i.e. to lower spatial frequencies). Such a lateral displacement would bring the binocular and monocular results displayed in Fig. 2 into register thereby accounting for the previously observed (i.e. Fig. 2) differential binocular/interocular filtering loss. Thus the fact that there is a differential loss of stereo acuity when lowpass filtering is applied to one eye's image compared to when it is applied to both eye's images equally, does not provide strong evidence against matching/stereo processing occurring within independent spatially tuned mechanisms. The fact that imbalances in the low spatial frequency content of images is not very disruptive (compared with similar filtering applied binocularly) for stereopsis for either Dmin or Dmax argues against the notion that matching occurs after combination of the output of spatially tuned mechanisms since such a manipulation would be expected to increase the number of false matches for zero-crossing or centroids. Quantitative predictions for such disruptions have been derived in the comparable case for motion in which differential spatial filtering is applied to different frames (as opposed to different eyes) in a two-frame motion (as opposed to stereo) sequence (Hess et al., 1998). In principle, the same shift (but in the opposite direction) in the interocular Dmax versus filter cutoff frequency function would have been expected for Dmax as explained above for Dmin. However, the effect of this would be much reduced because of the very shallow dependence of Dmax on the cutoff of the high-pass filter (Fig. 3).

4.2. Contrast

We show that neither Dmin nor Dmax was differentially disrupted when the maximum contrast was reduced in one compared with both eyes' images. The finding that contrast differences between the two eyes' images is no more disruptive than similar binocular contrast reductions implied that stereo performance is governed simply by the lower image contrast. Our results are at odds with previous research using 1-d, spatially narrowband stimuli (Halpern & Blake, 1989; Legge & Gu, 1989; Schor & Heckmann, 1989; Stevenson & Cormack, 2000) that has argued for a greater reduction in performance for interocular contrast differences. Our results however are consistent with the results of Cormack et al. (1997) using dynamic random element stimuli that show similar dependence of stereo acuity on monocular or binocular contrast reductions. Our results extend their original finding to Dmax as well as Dmin and further suggest that this is the case at all spatial scales for broadband images. This finding is not consistent with the suggestion made by Cormack et al. (1997) that it is the high spatial frequency content that enables broadband images to be less sensitive to interocular contrast differences. The more disruptive effect of monocular as opposed to binocular changes in contrast that have been reported previously for narrowband 1-d spatial stimuli (Halpern & Blake, 1989; Legge & Gu, 1989; Schor & Heckmann, 1989; Stevenson & Cormack, 2000) have been attributed to a number of causes, namely mutual inhibition between left and right eye monocular processes (Kontsevich & Tyler, 1994), correlations between noise components in left and right eye images (Legge & Gu, 1989), and contrast normalization within a single binocular filter (Stevenson & Cormack, 2000). Contrast normalization has been shown to occur for motion and is referred to as "motion contrast" (Georgeson & Scott-Samuel, 1999). It has recently been shown (Rainville, Scott-Samuel, & Makous, 2002) to be an inherently local process, operating within narrow spatial frequency and orientation bands. The present stereo results suggest that such an analysis cannot be applied to our broadband 2-d stimuli that contain a wide range of spatial frequencies and orientations. Contrast gain adjustments in the stereo case must involve a much broader pooling of spatial frequency and orientation information than has currently been shown for motion.

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