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The effects of blur and size on monocular and stereoscopic localization☆

Laurie M. Wilcox [a,*], James H. Elder [a], Robert F. Hess [b]

[a] *Centre for Vision Research, York University, 4700 Keele St., Toronto, Ont., Canada M3J 1P3*
[b] *McGill Vision Research, McGill University, Montréal, Quebec, Canada*

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Abstract

Monocular localization of non-abutting stimuli and stereoscopic localization of the same second-order targets are performed with the same precision (Wilcox, L.M. & Hess, R.F. (1996) Is the site of non-linear filtering in stereopsis before or after binocular combination? *Vision Research*, *36*, 391–399). Further, both tasks show a similar dependence on the scale of the stimulus. Since prior studies used Gaussian-enveloped stimuli, modifications of stimulus scale produced concurrent changes in edge blur. The experiments reported here assess the relative contributions of size and blur to the observed dependence on envelope scale for both monocular localization and stereoacuity. Stereoacuity for first-order targets was found to be an order of magnitude better than stereoacuity for second-order targets and monocular acuity for both first- and second-order targets. Further, while first-order stereopsis was found to depend solely on blur, second-order stereoacuity and monocular acuity were affected by both size and blur. These results suggest that while stereoacuity for first-order stimuli may be determined by a correlative process limited by early additive noise, stereoacuity for second-order stimuli and monocular acuity for non-abutting targets are more likely limited by stimulus-dependent spatial subsampling. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Both monocular localization and stereopsis are reported to use non-linear or second-order operations to provide position estimates. For stereopsis this second-order processing occurs under specific stimulus conditions. In contrast, for monocular localization it appears that the only requirement for second-order processing is that the stimuli be non-abutting (Burbeck, 1987; Toet, von Eekhout, Simons, & Koenderink, 1987; Toet & Koenderink, 1988; Kooi, DeValois, & Switkes, 1991; Hess & Holliday, 1992)[1].

Comparison of second-order stereopsis and monocular localization using the same stimuli and configuration has shown that the form of the non-linear operation used to extract the position estimate for these two tasks is similar (Wilcox & Hess, 1996). Performance for these 2D and 3D localization tasks shows the same dependence on the overall scale of the stimulus, and immunity to changes in the peak spatial frequency of the stimulus. However, to date only Gaussian enveloped stimuli have been used to assess second-order processing for both stereopsis and monocular localization. It is an inherent characteristic of these stimuli that as the size of the patch is varied, so too is the blur or slope of the edge at the boundary of the patch. It is possible that the degraded stereoacuity and monocular localization reported previously could be due not to a dependence on *size*, but to edge *blur*.

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* Corresponding author. Fax: +1-416-7465814.

E-mail address: lwilcox@yorku.ca (L.M. Wilcox).

[1] Monocular localization of abutting lines describes the well-known Vernier alignment task. There has been considerable investigation of this task in the literature, but it has been argued that because there are additional position cues available to aid in the alignment judgement (e.g. orientation and contrast) this task does not reflect a 'pure' localization judgement (see Hess & Holliday, 1992). In contrast, monocular localization of spatially separate targets provide no such additional cues therefore we will restrict our discussion of localization in this paper to that involving only non-abutting targets.

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This distinction is important to the development and evaluation of models for localization. Signal processing approaches often assume that the factor limiting performance is an early source of additive noise that can be modelled as Gaussian and white. Under these conditions, the optimal (maximum a posteriori) solution involves correlation followed by peak detection (Kay, 1998). For both simple first-order stimuli (e.g. luminance blobs or disks) and second-order stimuli, it is primarily the boundary of the stimulus that determines the accuracy of this approach. Since high spatial frequency components provide a more accurate localization signal than low spatial frequency components, the spatial frequency content of the boundary is crucial, and such a model would predict a decline in acuity as the boundary is blurred. However, since changing the size of the stimulus without changing the blur of the boundary has no appreciable effect on the high spatial frequency components, such a model would predict no effect of size on acuity. Observing an effect of size on acuity would therefore be interesting, and might reveal strategies of the visual system designed not necessarily to improve performance, but perhaps to limit computational complexity.

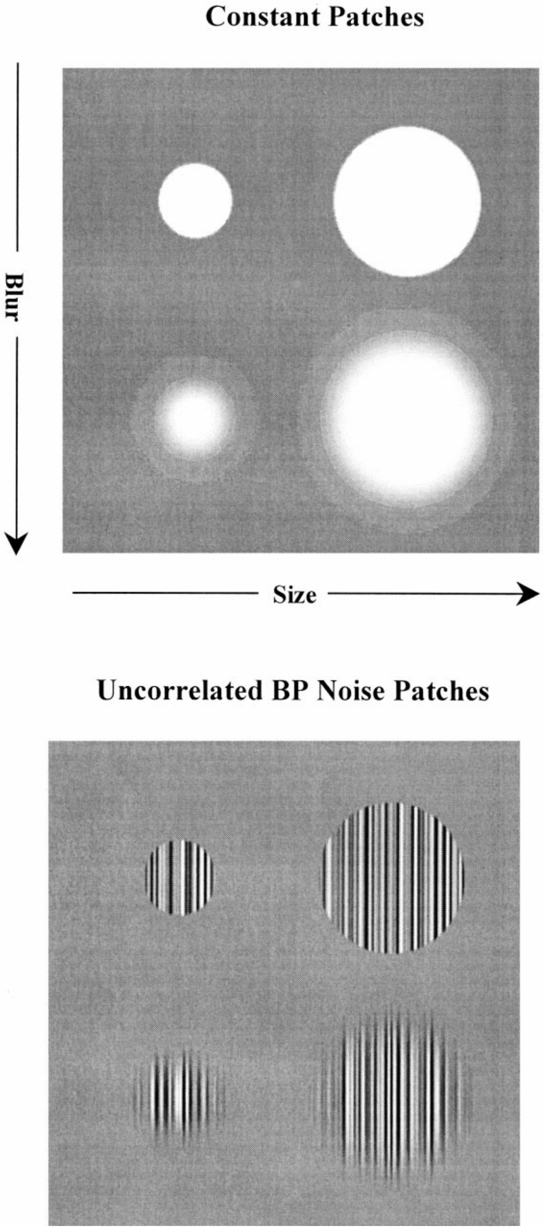

Fig. 1. Examples of the two stimuli used in the experiments reported here.

2. Methods

2.1. Subjects and apparatus

For each experiment extensive measurements were obtained using two experienced subjects. Subjects had excellent stereopsis and wore their prescribed optical correction. Stimuli were presented on a Joyce Electronics display screen with a P3 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. A Cambridge Research System (VSG2/1) graphics card was used to generate and display the stimuli. The mean luminance of the display, as viewed through the liquid crystal shutters, was approximately 49 cd/m^2.

Stereoscopic depth was achieved using ‘Display Tech’ liquid crystal shutters mounted in trial frames. The stimuli for each eye were presented on alternate frames at a rate of 200 Hz (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.

2.2. Stimuli

To investigate the separate roles of blur and size in both first- and second-order stereopsis, two types of stimuli were employed (Fig. 1)

1. Constant patches. Patches of constant intensity, blurred (convolved) with a two-dimensional Gaussian kernel.
2. Noise patches. Constant patches multiplied by one-dimensional bandpass noise. The Gaussian i.i.d. noise process and bandpass filter were both horizontal, creating random vertical stripes. The filter employed was a one-dimensional Gabor function, with sinusoidal period of 18.6 arc min and Gaussian scale constant of 4.27 arc min, forming a bandpass kernel of peak frequency 3.23 cpd and bandwidth of 1.89 octaves.

The stimuli were designed to allow *independent* manipulation of size and blur. Size was varied by manipulating the diameter of the generating constant patch and three sizes (diameters of 1.3, 2.7, and 5.3 deg) were

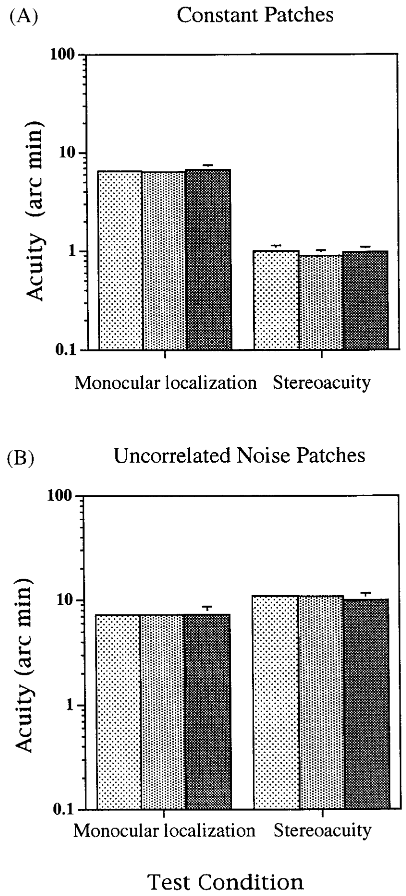

Fig. 2. Stereoacuity and monocular localization for one subject, two stimuli (constant disks in (A), and uncorrelated noise in (B)) and three reference conditions. In one condition (dotted bars) the reference was identical to the mid-sized constant patch with an edge-to-edge separation of approximately 1 deg. In the remaining conditions the reference was a bar with a width of 1 deg and an edge to edge separation from the target of approximately 4 deg (light grey bars) or 1 deg (dark bars). Error bars indicate ± 1 S.E. of the mean.

employed. Blur was varied by manipulating the scale constant of the Gaussian blur kernel. Four blur scales were employed (Gaussian scale constants of 2.3, 11.6, 37.1, and 58.0 min), although for technical reasons the higher blur values could not be used for all conditions (Section 2.3).

The stimulus arrangement was the same for all conditions, except for those involving the largest (5.3 deg) patches, for which an alternate arrangement had to be employed due to limited screen size. In the standard arrangement, subjects viewed two vertically aligned patches. The upper patch provided the zero disparity reference plane, while the lower patch was shifted laterally or in depth. For the experiment involving constant patches, the reference stimulus was identical to the test stimulus. However, for experiments involving the uncorrelated noise patches the reference stimulus consisted of left and right eye versions of the same noise sample (perfect correlation), while the test stimulus consisted of independent noise samples. Several different schemes for fixing the vertical separation of reference and test patterns were considered. Rather than fix the absolute distance between patch centers or (nominal) boundaries we chose to fix the spacing of the patches *relative to their size*. This design has the advantage that, in relative terms, both the center-to-center and the edge-to-edge spacing remained constant. Thus the stimulus arrangement for smaller stimuli was as that for larger stimuli viewed from a greater distance.

Toet et al. (1987) evaluated the effect of separation on monocular localization using a wide range of separation distances, and found that the influence of separation on acuity only occurred at separations larger than 25 times the size (scale constant σ) of their Gabor stimuli. Hess and Wilcox (1994) evaluated the effect of separation on stereoacuity using Gabor patches and found that there was no effect of increased separation over a substantial range. In the experiments reported here the absolute difference in separation of the small and large patches was never greater than a factor of 4. Thus we were well within the range where both of these studies found no effect of separation on performance. It is therefore unlikely that the effects of size reported here can be attributed to changes in separation between the target and reference. Additional support for this argument can be seen in Fig. 4A, which shows no effect of stimulus size on stereoacuity at any stimulus blur. If absolute separation and not stimulus size were determining performance in Fig. 4B, Fig. 5A and B, it should do so for all test conditions.

For the largest (5.3 deg) patches, it was not possible to display both stimuli simultaneously, so the upper patch was replaced with a bar that extended to the edge of the display. The dimensions of this reference bar were a constant fraction of the diameter of the target stimulus; the width was one quarter the target diameter, and the edge of the bar and the target were separated by one stimulus diameter. To be certain that this modification had no effect on the pattern of results, a control experiment was performed where monocular localization and stereoacuity were assessed using the 2.7 deg constant patch and uncorrelated noise patch, and three reference configurations. Results for one subject are shown in Fig. 2.

As is evident from Fig. 2, there was no effect of the form of the reference stimulus on stereoacuity or monocular localization in either the constant disk ($F = 0.09$, $P > 0.01$) or noise disk ($F = 0.08$, $P > 0.01$) conditions as assessed using ANOVA procedures.

2.3. Procedure

2.3.1. Size matching

Our goal was to measure the effect of size on acuity when blur is fixed and to measure the effect of blur on acuity when size is fixed. Since the perceived size of a patch will vary with the extent to which it is blurred, we selected the diameters of the size-fixed stimuli through a subjective size-matching procedure so that the stimuli were of equivalent *perceived* size. Using a modified method of adjustment procedure, subjects were asked to match the size of a blurred patch to that of a relatively unblurred (blur scale constant of 2.3 min)[2] reference patch of the same type and standard size (1.3, 2.7, or 5.3 deg). Preliminary matching experiments showed that the effect of blur on perceived size was negligible for the two smallest blur scales employed (2.3 and 11.6 min). Thus size matching was only performed for the larger blur scales (37.1 and 58.0 min).

2.3.2. Contrast thresholds

Contrast thresholds were measured at two stages of the experiment: prior to size matching, and before acuity testing. In both instances, we used the method of adjustment with a randomized starting point to obtain seven binocular threshold estimates, which were then averaged. The subsequent test contrast was set at 15 dB above this value.

2.3.3. Localization

In the stereoacuity experiments we measured the precision with which a single patch could be localized in depth relative to a zero disparity reference stimulus; in the monocular localization studies we assessed the precision with which lateral offsets in the target position relative to the reference could be detected. The only difference between the two conditions was the nature of the localization judgement that is: front/behind vs. left/right.

Localization was measured using the method of constant stimuli, and a set of 11 test values. Stimuli were presented within a temporal raised cosine of total duration of 1 s and so were visible for approximately 0.3 s. The observers' task was to identify on each trial whether the central target was positioned in front of or behind (3D) or to the left or right (2D) of the reference stimulus. Within a single run each of the offsets were presented 20 times in random order. A localization estimate was derived from the resulting psychometric function, by fitting the error function (cumulative normal), ERF (x), of the form:

$$P(x) = \frac{A}{2}\left(1 + \mathrm{erf}\left(\frac{x-B}{\sqrt{2}C}\right)\right)$$

The S.D. parameter C was employed as the measure of localization: it increases as performance deteriorates. Each datum represents the average of at least three such estimates from which the S.E. of the mean was estimated.

3. Experiment 1 — stereoacuity

3.1. Constant patches

Based on the results of our previous experiments we predicted that the constant patches used here would stimulate the first-order stereoscopic system, so performance should depend largely on the spatial frequency content of the stimulus. The effects of blur and size on the spatial frequency content of the constant patch stimuli can be seen most clearly if we can collapse the two-dimensional Fourier spectrum into a one-dimensional plot. Since the interocular shift is strictly horizontal, we take the one-dimensional Fourier transform of each horizontal scanline through the stimulus independently, and then sum the stimulus power at each frequency across the set of scanlines. The resulting one-dimensional spatial frequency plots are shown in Fig. 3A.

Simply blurring the stimulus reduces the stimulus energy at high frequencies, while preserving the energy at low frequencies. Increasing the size of the stimuli, on the other hand, primarily boosts the low spatial frequencies. It is important to note, however, that in our experiments the contrast of each stimulus was adjusted to maintain its visibility. Since blurring was found to reduce visibility, contrast was increased as a function of blur. The net effect of blur, therefore, was to *increase* the energy at low spatial frequencies in addition to attenuating energy at higher frequencies. However, changes in stimulus diameter did not greatly affect stimulus visibility, therefore, stimulus contrasts were relatively constant and the primary effect of increasing stimulus size was to boost the lowest spatial frequencies.

It is widely accepted that conventional (first-order) stereoacuity improves with increasing spatial frequency, up to at least 2.5 cpd (Schor & Wood, 1983). This finding is consistent with the hypothesis that first order stereopsis is based upon an interocular correlation limited by internal additive white noise: a given error in binocular registration produces a greater reduction in the interocular correlation signal for a high spatial frequency grating than for a low frequency grating. Based on this analysis, one would predict that while blurring the stimuli will reduce stereoacuity, dilating the stimuli will have a limited effect. Fig. 4A shows that these predictions are confirmed.

Stereoacuity for these constant patches is not affected by stimulus size (LW: $F=0.266$, $P>0.01$ AW: $F=5.47$, $P>0.01$) but there is a significant main effect of blur (LW: $F=132.97$, $P<0.01$ AW: $F=57.31$, $P<0.01$). For the three blur scales tested (2.3, 11.6, and 37.1 min), filtering attenuates the 2.5 cpd component of the stimulus by 0.9, 21 and 91%, respectively, thus this result is at least qualitatively consistent with the 2.5 cpd limit reported by Schor and Wood (1983).

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[2] This is approximately the minimum blur required to reduce pixel aliasing artefacts to below perceptual threshold.

3.2. 1D noise patches

In this study we use a stimulus designed to activate only second-order processing: uncorrelated noise patches. Previous results with similar stimuli have shown that when stereoacuity is assessed using Gaussian-enveloped, uncorrelated noise patches, performance depends only on the overall scale of the patch (Wilcox & Hess, 1996). The observed dependence on stimulus scale could be due to either the change in the size of the stimulus, or to the corresponding variation in the blur of the stimulus boundary.

The results of this experiment are shown in Fig. 4B; comparison with Fig. 4A shows that while there is still an effect of blur on stereoacuity there is now a clear effect of stimulus size that was not observed in the previous test condition. Analysis of variance confirms these observations for both subjects with a main effect of blur (LW: $F = 4.98$, $P < 0.01$ AW: $F = 116.09$, $P < 0.01$) and of size (LW: $F = 9.06$, $P < 0.01$ AW: $F = 15.88$, $P < 0.01$). These results clarify previous results by showing that *both* size and boundary blur play a role in determining the precision of second-order stereopsis (Wilcox & Hess, 1995, 1996, 1997).

Can these results be explained by the spatial frequency content of the noise patch stimuli? To analyze the spatial frequency content of the noise patches, we considered the sum of their spectral density across horizontal scanlines (Fig. 3B). Blurring per se has little effect on the spatial frequency content of the stimulus, although the effects of adjusting contrast for comparable visibility produced an overall increase in the power

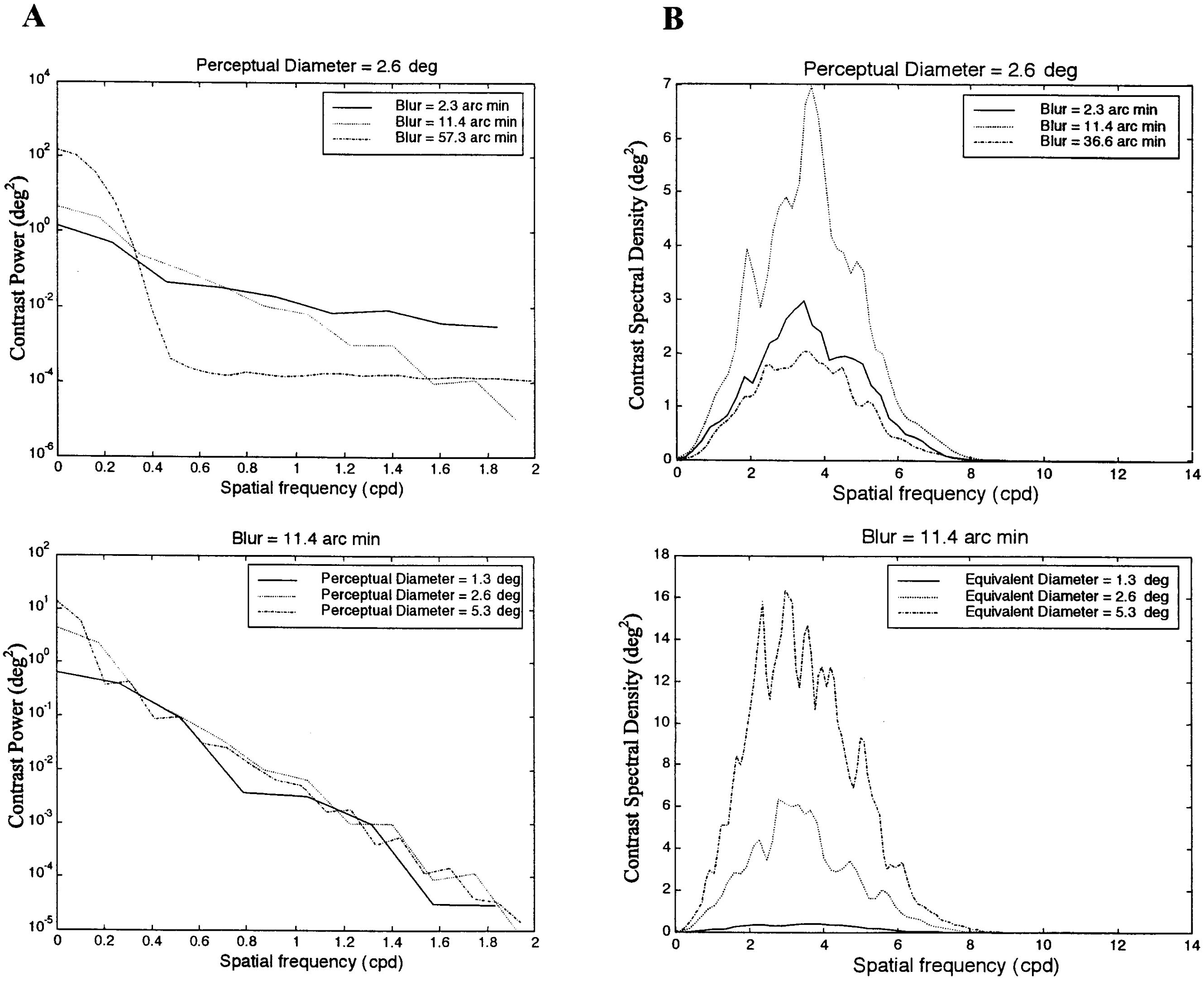

Fig. 3. Spatial frequency content of the stimuli used in our experiments. The top plots show the effect of blur for the stimuli of intermediate size. The bottom plots show the effect of size for the stimuli of intermediate blur. (A) Horizontal power spectrum for constant patch stimuli. (B) Horizontal spectral density for the noise patch stimuli. Fifty samples of the two-dimensional stimuli were used to estimate the spectral density. Note that the spectra reflect the adjustments in contrast made to the stimuli to maintain consistent stimulus visibility (see text).

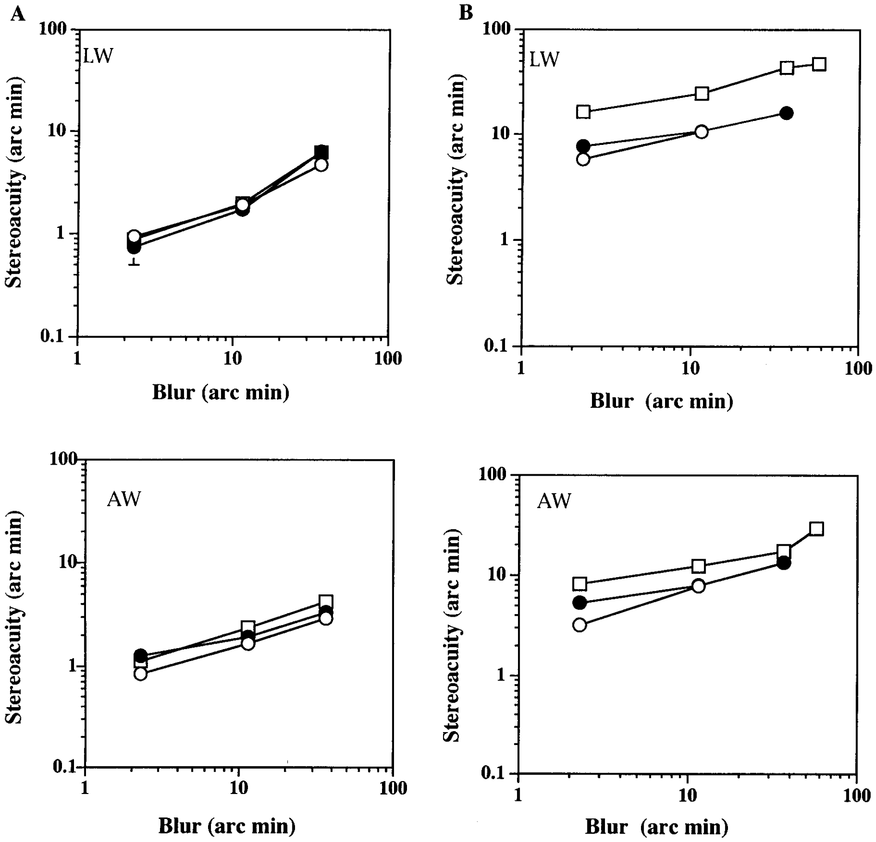

Fig. 4. Stereoacuity is shown here as a function of stimulus blur for constant patches (A) and uncorrelated noise patches (B), for two subjects and three stimulus sizes. The diameters of the pre-filtered patches were 1.3 deg (○), 2.7 deg (●) and 5.3 deg (□). S.E. bars represent ± 1 S.E. of the mean, and where invisible are smaller than the size of the symbol.

over all frequencies for the intermediate blur condition. Dilating the stimulus window, on the other hand, produces a massive *increase* in stimulus energy at all frequencies. Based on a superficial analysis of spatial frequency content, one might predict that whereas blurring would have little effect on stereoacuity, increasing the size of the stimuli would greatly *improve* stereoacuity. Instead, our results show that stereoacuity *degrades* substantially when either blur or size is increased. The failure of a spatial frequency analysis to predict stereoacuity for the noise patches is not surprising given that the stimuli are binocularly uncorrelated, and so increasing the energy of the stimuli does not necessarily make the correspondence problem easier to solve. In particular, it seems unlikely that early visual noise is the limiting factor for these stimuli, as we have assumed for the constant patches; it is more likely that uncertainty in correspondence arises from the noisy nature of the stimuli themselves.

4. Experiment 2 — monocular localization

There is evidence that monocular localization for non-abutting, narrow-band stimuli relies on second-order localization signals. In these studies performance is not influenced by the spatial frequency content of the patches, but is affected by changing their overall scale (Burbeck, 1987; Toet et al., 1987; Hess & Holliday, 1992). Again, this dependence could be due either to an effect of size or of the blur of the stimulus boundary.

It has been proposed that second-order stereopsis and large scale monocular localization for non-abutting targets use a similar non-linear operation to extract position information (Wilcox & Hess, 1996). To determine whether this congruence holds over variations in both blur and size, we measured monocular localization using our first- and second-order stereoscopic stimuli (constant patches and 1D noise patches). Assuming that monocular localization for non-abutting targets is based on the same second-order position signals used for second-order stereopsis, we can expect that blur and size should have the same influence on monocular localization as they have on second-order stereopsis. Comparison of Fig. 4B with Fig. 5A and B supports this prediction.

Monocular localization results for constant and 1D noise patches are similar, and most closely resemble the pattern of results obtained for second-order stereopsis (Fig. 4B). Performance is clearly degraded by both increasing blur and size. Analysis of variance confirms this: there are main effects of both blur (LW: $F = 29.7$, $P < 0.01$ AW: $F = 8.83$, $P < 0.01$) and size (LW: $F = 114.97$, $P < 0.01$ AW: $F = 18.39$, $P < 0.01$) for the constant disks. Similar main effects of blur (LW: $F = 10.43$, $P < 0.01$ AW: $F = 43.02$, $P < 0.01$) and size (LW: $F = 12.98$, $P < 0.01$ AW: $F = 17.06$, $P < 0.01$) were found for the uncorrelated noise stimuli.

The decline in monocular acuity with the blur of the constant patches is qualitatively consistent with a spatial frequency analysis of the stimulus, assuming an internal noise-limited correlation-like computation (Section 3). However, such an analysis cannot explain the decline in acuity with increasing stimulus size. Nor can it explain the effects of blur and size on acuity for the noise stimuli.

5. Discussion

It is clear that the relative effects of size and boundary blur on 2D and 3D localization performance depends critically on the stimulus used and its configuration. Stereopsis assessed using first-order stimuli (constant patches) is unaffected by changes in stimulus size, but depends on edge blur. This finding is consistent with a model based on noise-limited interocular correlation. Importantly we have shown here that there is an effect of *both* blur and size on second-order stereoacuity for uncorrelated noise patches, a result that has not previously been reported. Monocular localization for non-abutting targets, similar to second-order stereopsis, is also degraded by both edge blur and an increase in stimulus size. These results raise a number of questions that we address below.

5.1. Why is stereoacuity much better for constant patches than for uncorrelated noise patches?

We have recently reported an ideal observer analysis of stereoacuity for constant and uncorrelated noise patches (Elder & Wilcox, 2000). Assuming an early internal source of additive white noise, the ideal observer for the constant patches performs a global interocular correlation. The ideal observer computation for the binocularly uncorrelated stimuli is quite different from this computation, and suffers from additional uncertainty due to the multiplicative noise process inherent in the stimulus. We believe that this stimulus noise is the main factor determining stereoacuity for the binocularly uncorrelated noise patches. This hypothesis is supported by a previous finding that second order

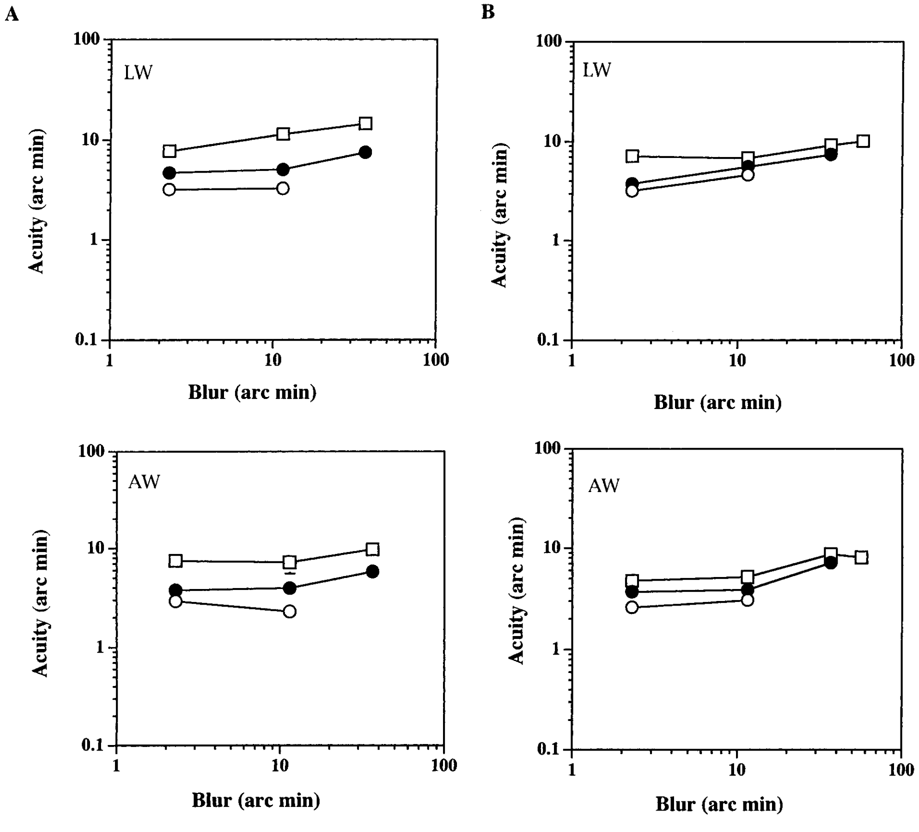

Fig. 5. Monocular localization acuity is plotted as a function of blur for two subjects using constant patches (A) and uncorrelated noise patches (B). The three functions represent stimulus diameters of 1.3 (○), 2.7 (●) and 5.3 (□) deg. S.E. bars represent ± 1 S.E. of the mean, and where invisible are smaller than the size of the symbol.

stereopsis is unusually insensitive to stimulus contrast (Wilcox & Hess, 1998).

It is possible that second order stereopsis is also based on an interocular correlation process, but preceded by some form of point nonlinearity. Indeed we have demonstrated that rectification and a square root nonlinearity in suprathreshold contrast prior to correlation can explain the general level of human performance in second-order stereoacuity tasks (Elder & Wilcox, 2000).

5.2. Why is stereoacuity for constant patches much better than monocular acuity for constant patches?

This pattern of results has been described in the past by Wilcox and Hess (1996), who demonstrated that not only was performance poorer for both 2D and second-order 3D localization, but that they shared the same dependence on stimulus scale. But *why* is localization performance so much poorer for monocular localization? The ideal observer computations for these tasks are very similar: both are based on correlation. Thus an ideal observer analysis would predict similar performance on these two tasks. The large difference in performance therefore suggests that the two problems are solved using quite different computational mechanisms. Whereas the sensitivity of first-order stereoacuity to high spatial frequency content and contrast is consistent with a correlation mechanism, the insensitivity of monocular acuity to these factors argues against such a mechanism for monocular localization.

Why would correlation not be used for monocular localization? An obvious reason is the computational cost. Whereas stereopsis requires correlation along only the horizontal dimension, monocular alignment problems may be faced along any one of an infinite number of retinotopic axes. Replicating dedicated hardware to cover all possibilities would be prohibitively expensive. While correlation involves a point-to-point comparison between two stimuli, a computationally cheaper solution to monocular localization is to extract a position estimate of each stimulus first, and then to compare these two estimates to each other to determine alignment. A relatively robust way to represent the position of a stimulus is by its centroid. However, centroid computations are dependent upon the size and shape of the window within which the computation is restricted: one needs a method for selecting the appropriate window size. One possible solution to this problem is to use the concept of local scale control (Elder & Zucker, 1998), selecting the minimum window size producing a centroid estimate that is relatively insensitive to small perturbations in the location of the window. Such a multiscale computation will demand computational resources, and in order to control these costs images must be subsampled at larger scales. This subsampling could explain the poorer level of performance for monocular acuity relative to first order stereopsis.

5.3. Why do stereoacuity and monocular acuity decline with blur for both constant and noise patches?

High spatial frequencies are inherently more important to localization (assuming internal white noise) than low spatial frequencies. For the constant patch stimuli, blurring reduces the high spatial frequencies, and so the decline in acuity is expected. Blurring the boundary of the noise stimuli does not substantially affect the energy in the high spatial frequencies of the overall stimulus. However most of this energy is not useful for localization, as the interocular correlation of these Fourier components is near zero. It is important to note that the localization signal is in fact provided by the stimulus window, so that if the high frequency components of the window are attenuated, it is to be expected that acuity will decline.

5.4. Why does stimulus size affect stereoacuity for binocularly uncorrelated noise patches (but not for constant patches) and monocular acuity for both types of stimuli?

Since stimulus size does not substantially alter the high spatial frequency content of the constant patch stimuli, a correlation-based model would predict little effect of size on stereoacuity for the constant patches. The decline in monocular acuity with stimulus size is consistent with a centroid computation involving scale-dependent spatial subsampling (Section 5.2). The fact that stereoacuity for uncorrelated noise patches also declines with increasing stimulus size also suggests a scale-dependent computation. One possibility is that correlations are not entirely global, but are performed at a variety of correlation scales. As for centroid computation, a reliable scale must be selected, and this is likely to depend upon stimulus size (Elder & Wilcox, 2000). Assuming spatial subsampling to control computational cost, such a mechanism would predict a similar decline in stereoacuity for larger (second-order) stimuli.

5.5. Do these findings help to discriminate between existing models for stereoscopic and monocular localization?

A correlation-based model (e.g. Cormack, Stevenson, & Schor, 1991; Harris, McKee, & Smallman, 1997) is consistent with our stereoacuity results for constant patches. With some nonlinear adaptations, it appears that a correlation-based model could also account for second order stereopsis (Elder & Wilcox, 2000).

The dependence of second-order stereoacuity and first- and second-order monocular acuity on stimulus size supports the hypothesis that localization estimates are made at multiple spatial scales (Marr & Poggio, 1979; Watt & Morgan, 1983; Heckmann & Schor, 1989; Harris et al., 1997)

Some means for discriminating between reliable and unreliable scales for a given stimulus is needed; one candidate for such a reliability criterion for stereopsis is a disparity gradient limit constraint (Pollard, Mayhew & Frisby, 1985).

The centroid model for monocular localization has been proposed by a number of investigators (Westheimer & McKee, 1977; Watt & Morgan, 1983; Toet & Koenderink, 1988; Hess & Holliday, 1996). Such a model would require some elaboration to account for the observed decline in acuity with stimulus size. One possibility is a multi-scale, sub-sampled centroid computation, with scale selection based upon spatial centroid stability. Models based upon a correspondence of features such as peaks, troughs, derivative zero-crossings or peaks in linear filter responses (Toet & Koenderink, 1988; Legge & Gu, 1989; Hess & Holliday, 1992) are unlikely to explain second order localization, as such models would compute essentially random correspondences between uncorrelated stimuli. Mechanisms based upon local phase (Ohzawa, DeAngelis, & Freeman, 1990) would also fail, unless they included a scale-adaptive mechanism that could select filters on the same scale as the stimulus (up to 5.3 deg). Models for stereopsis based upon matching peaks and troughs (Legge & Gu, 1989) are also inconsistent with the fine first-order stereoacuity observed in our experiments with constant patch stimuli, since these stimuli have no well-defined peaks or troughs.

5.6. Relation to previous experiments

5.6.1. The effect of blur on stereoscopic localization

There is considerable evidence that increased edge blur degrades stereoscopic localization. Stigmar (1971) used ground glass to blur line targets and found that both stereoacuity and Vernier alignment acuity degraded with increasing stimulus blur. Westheimer and McKee (1980) conducted a more thorough study comparing the effects of blur on monocular resolution (snellen acuity) and stereoacuity and found both to degrade with blur. More generally, there is substantial evidence for sensitivity of stereoacuity to the spatial frequency composition of the stimulus (Julesz & Miller, 1975; Schor & Wood, 1983; Heckmann & Schor, 1989).These results are consistent with the observed effects of blur on stereoacuity for the constant patches used in our experiments.

5.6.2. The effect of size on localization

There is considerable evidence for the size-disparity correlation originally proposed by Felton, Richards, and Smith (1972) and later supported by, among others Schor and Wood (1983), Smallman and MacLeod (1994). It is important to note that there has been a tendency in the literature to equate stimulus size and spatial frequency. While it is true that the width of the bars of a sinusoidal grating varies inversely with spatial frequency, no such straightforward relationship exists for broadband targets such as lines, or in our case, disks. Moreover, the focus on stimulus spatial frequency has lead some investigators to overlook the potential effect of the overall spatial extent of the stimulus. For example Schor and Wood (1983) measured stereoacuity for difference of Gaussian (doG) patterns as a function of their centre frequency. They reported that performance improved with increasing spatial frequency up to 2.5 c/deg and then reached a plateau. However, they did not consider that the overall size of the doG varies inversely with its centre frequency. Thus it is not immediately clear if their pattern of results should be attributed in part to a change in stimulus size. Hess and Wilcox (1994), Wilcox and Hess (1995) avoided this problem by using Gabor stimuli, which allowed stimulus size and centre frequency to be independently manipulated. However they did not consider the effect of edge blur, which would also have contributed to the degradation of stereoacuity observed in their studies.

Toet et al. (1987) measured the effect of separation on monocular localization for Gaussian stimuli over a range of scales. They discuss their results in terms of the scale invariant nature of the effect of separation, but refer consistently to the blur of the stimulus edges. They do not mention the concurrent variation of stimulus size. Thus it is not clear whether the interaction they observe is due to size-scaling, or blur-scaling. In a subsequent experiment (Toet & Koenderink, 1988) the opposite omission is made: the effect of envelope size on monocular localization is discussed, while the concurrent changes in edge blur are ignored (see also Hess & Holliday, 1992). The results of our experiments show that both sets of data likely reflect the *combined* effects of the change in size and edge blur.

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