PERGAMON

Vision Research 38 (1998) 3671–3679

Vision Research

# When stereopsis does not improve with increasing contrast[1]

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

[a] *York University, Department of Psychology, 4700 Keele Street, North York, Toronto, Ontario M3J 1P3, Canada*
[b] *McGill Vision Research, McGill University, Montreal, QC, Canada*

Received 24 September 1997; received in revised form 4 February 1998

---

**Abstract**

It is well known that stereoacuity for conventional (1st-order) stimuli improves with increasing contrast with an approximate slope of −0.5 on log–log axes (Halpern DL, Blake RR. Perception 1988;17:483–495; Legge GE, Gu Y. Vis Res 1989;29:989–1004). In the experiments reported here a variety of stimuli were used (Gabor patches, amplitude modulated stimuli and 1D noise patches) and tasks (stereoacuity and $D_{\max}$) to determine if 2nd-order stereopsis shows a similar square root dependence. The results consistently demonstrate that the effect of contrast on stereopsis is quite different for the 2nd-order stimuli. Increases in stimulus contrast have little effect on performance; the resulting slopes are very shallow. The pattern of results is similar when the interocular contrast ratio is varied, demonstrating that 2nd-order processing is more resilient to stimulus differences in the two eyes than 1st-order. © 1998 Elsevier Science Ltd. All rights reserved.

*Keywords:* Stereoacuity; $D_{\max}$; Contrast; 2nd-order; Non-linear

---

## 1. Introduction

In close succession, both Halpern and Blake [1] and Legge and Gu [2] reported a consistent dependence of stereoacuity on contrast for tenth derivative of Gaussian ($D_{10}$) and sinusoidal grating stimuli, respectively. These two sets of experiments provide convincing evidence that for a range of test conditions the slope of this relationship is near −0.5 with Legge and Gu [2] reporting an average slope of −0.54, and Halpern and Blake [1] an average slope of −0.67, on log–log axes. Legge and Gu's results seem to show a high degree of variability, with slopes ranging from −0.38 to −0.84. However, this variability could also reflect the fact that they tested a range of spatial frequencies. There is an indication in Halpern and Blake's results that steeper slopes are obtained for lower frequencies; a result that has recently been verified by Cormack et al. [3]. The data reported by Legge and Gu [2] and Halpern and Blake [1] were obtained using stimuli that stimulate 1st-order stereoscopic processing. This is the conventional sort of stereopsis that has been studied for centuries, and is known to also depend on the orientation and spatial frequency content of the stimulus [4–8].

More recently a number of investigators have reported evidence that non-linear or 2nd-order information is also used by the stereoscopic system [9–20]. This mode is so named because it extracts the disparity signal provided by the contrast envelope of the stimulus, and it is immune to changes in the luminance spatial frequency content. While it is widely accepted that 1st-order stereopsis is contrast dependent, little is known about the effect of contrast on 2nd-order processing of depth information. To remedy this the experiments reported below assess stereopsis under a variety of conditions designed to activate either 1st- or 2nd-order processing. For each of these tasks and stimuli we measure the contrast dependence of stereopsis and compare that relationship to similar conditions when the 1st-order system determines performance. A final experiment examines the effect of varying the interocular contrast ratio to determine if 2nd-order stereopsis exhibits the same sensitivity to dichoptic contrast variation as previously reported [1,2].

---

* Corresponding author. Fax: +1 416 7365814; e-mail: lwilcox@yorku.ca.

[1] Portions of this work were presented at The European Conference on Visual Perception, Helsinki, 1997.

PII: S0042-6989(98)00066-2

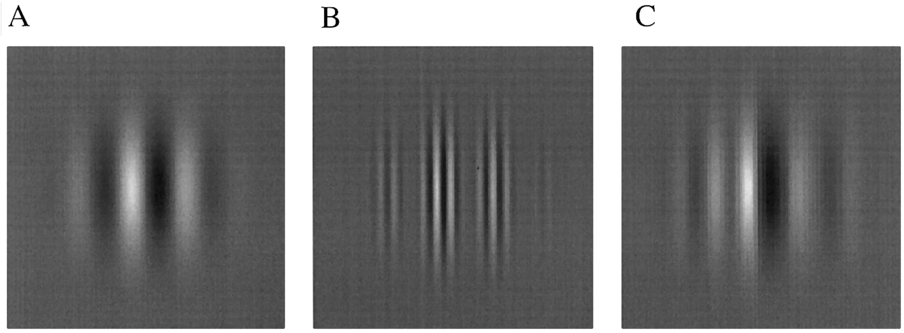

Fig. 1. The three types of stimuli used here were Gabors (A) amplitude-modulated Gabors (B) and uncorrelated noise (C). Unless stated otherwise the $\sigma = 0.38°$ in all cases and the separation was fixed at four times $\sigma$ or 1.5°.

## 2. Methods

### 2.1. Subjects and apparatus

Extensive measurements were obtained from two experienced subjects. Both subjects had excellent stereopsis as assessed using the Randot Stereotest and by their performance in previous stereoacuity experiments. Both subjects 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. The mean luminance of the display, viewed through the shutter glasses, was approximately 45 cd/m$^2$. To verify the linearity of our display system we drifted a complex pattern past a narrow slit and measured the luminance at each pixel using a UDT photometer. We then examined the power spectrum of the stimulus. This procedure was repeated at a number of positions on the display and revealed no evidence of distortion.

Stereoscopic depth was achieved using 'Display Tech' liquid crystal shutters mounted in trial frames[2]. A ±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.

#### 2.1.1. Stimuli

Fig. 1 shows the three different types of stimuli used to assess the effect of contrast on stereopsis. For the sake of simplicity, they are described in greater detail in the relevant sections. The stimulus arrangement was the same in all cases. That is, three stimulus patches were aligned vertically. The two peripheral stimuli, located directly above and below the central stereo-target, provided a stable fusion stimulus and reference plane. The distance between the target and the reference stimuli was held constant at approximately four times the standard deviation of the Gaussian.

#### 2.1.2. Procedure

Contrast thresholds were measured prior to testing and for each condition the contrast of all three patches was set at a given amount above this value. For all contrast measurements, we used the method of adjustment with a randomized starting point to obtain seven binocular threshold estimates which were then averaged. 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).

#### 2.1.3. $D_{max}$

$D_{\max}$ was measured using the method of adjustment[3]; the stimulus disparity was gradually increased in 1 pixel steps from a quasi-randomly selected initial offset, until the upper limit for stereopsis was reached. The angle subtended by one pixel varied with viewing distance such that at 0.25, 0.5, 1.0, 2.0 and 4.0 m one pixel equalled 9.16, 4.58, 2.29, 1.145, and 0.57 arc min, respectively. The starting disparity for the method of

---

[2] The liquid crystal shutters allow a very fast alternation rate, which can be faster than the decay time of a monitor's phosphor(s). In some situations (e.g. high contrasts) this results in cross-talk, or leakage, between the two eyes views. This problem was avoided by ensuring that for most conditions the contrast was below that required to detect the cross-talk [28]. Further, in all conditions disparity offsets were so small that ghost images were masked by the stimulus in the other eye.

[3] In a previous set of experiments we measured $D_{\max}$ using the method of adjustment, and a more rigorous staircase procedure in which hysteresis was avoided, and both crossed and uncrossed disparities were interleaved. The results obtained using the two methodologies were identical, thus verifying that the method of adjustment is appropriate for this task.

adjustment was varied randomly by several pixels on separate trials to insure 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 are shown here for crossed disparities only. However, in another publication we report $D_{\max}$ as a function of viewing distance, carrier spatial frequency and envelope size for both crossed and uncrossed disparities, using an interleaved staircase method [13]. For subject LW crossed and uncrossed performance is identical; subject JH exhibits lower $D_{\max}$ values for crossed disparities, but this difference is consistent across all test conditions. Thus we are satisfied that the results shown here are representative.

#### 2.1.4. Stereoacuity

Stereoacuity was measured using the method of constant stimuli, with a set of 11 stimuli which covered a range of crossed and uncrossed disparities. This range was chosen individually for each stimulus condition to bracket the point at which the perceived location of the central stimulus changed from being ‘in front’ to ‘behind’ the peripheral patches. When required, sub-pixel spatial accuracy was achieved by recomputing each newly located stimulus instead of simply repositioning the stimulus in graphics memory. The stimuli were presented within a temporal raised cosine of total duration 1 s; stimuli 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 the two outside stimuli and within a single run each of the depth offsets were presented 20 times in random order. A stereoacuity estimate was derived from the resulting psychometric function, by fitting the error function (cumulative normal), ERF ($x$), of the form:

$$P(x) = A(0.5 + 0.5\,\mathrm{ERF}((x - B)/(\sqrt{2.0}C))) \tag{1}$$

where $A$ is the number of presentations per stimulus condition, $B$ is the offset of the function relative to zero, and $C$ is the standard deviation of the assumed underlying, normally distributed, error function. This standard deviation parameter serves as an indicator of stereothreshold for as it increases, stereoacuity declines. Each datum represents the average of three such estimates from which the standard error of the mean was derived.

## 3. Experiment 1: $D_{\max}$ as a function of contrast

It is well-known that a strong percept of ‘qualitative’ depth is possible well beyond the fusion limit, with diplopic stimuli [21]. In a previous study [13] we used Gabor stimuli to measure the upper disparity limit and found that performance was virtually unaffected by 1st-order information, that is, the spatial frequency content of the stimulus, but see also [22]. Instead, $D_{\max}$ was determined by 2nd-order information (i.e. attributes of the stimulus envelope) and so will provide a good initial test of the effect of contrast on 2nd-order stereopsis.

### 3.1. Stimuli

The stimuli were patches of sinusoidal grating multiplied by a symmetric 2-dimensional Gaussian (Fig. 1A). The grating component of each stimulus was oriented vertically. The form of the Gabor function was:

$$L(x, y) = A\ \exp\left(\frac{-((x - x_0)^2 + y^2)}{2\sigma^2}\right)\sin(2\pi x/T) \tag{2}$$

where $A$ is the amplitude of the function, $\sigma$ is the standard deviation of the Gaussian envelope defining the patch, $x_0$ represents the disparity offset which was in equal and opposite directions in each eye, 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 stimuli.

$D_{\max}$ was measured as a function of contrast, for a range of stimulus sizes ($\sigma = 11.5$, 23, 46 arc min). The size of the patch was varied by changing the viewing distance to the screen. Although this manipulation also affected the centre frequency of the Gabor patch, as noted above, performance on this task is not influenced by the spatial frequency content of the stimulus.

### 3.2. Results and discussion

We have plotted $D_{\max}$ as a function of contrast (in dB above detection threshold) for both subjects and for a range of stimulus sizes $\sigma = 11.5$ (○), 23 (■), and 46 (●) min, in Fig. 2. It is clear from the data that increasing the stimulus contrast does not cause any systematic increase in $D_{\max}$, in fact for subject LW there is a slight decrease in $D_{\max}$ at the highest contrasts at all sizes, while JH’s results are more variable.

The data presented in Fig. 2 demonstrates convincingly that the upper disparity limit is not increased by raising the contrast. Since we know that this task is performed by way of 2nd-order information, these results provide preliminary evidence that 2nd-order stereopsis does not have the same contrast dependence as 1st-order stereopsis (assessed using stereoacuity measures). The aim of the subsequent set of experiments is to determine if the contrast dependence for a specific stimulus can be made to change depending on which type of disparity information is used to do the task.

## 4. Experiment 2: stereoacuity as a function of contrast

### *4.1. Introduction*

The data presented in the first experiment suggests that the contrast dependence for 2nd-order stereopsis is much weaker than that typically observed under 1st-order test conditions. A more rigorous test of this difference is to assess the contrast dependence of stereopsis for similar stimuli under 1st- and 2nd-order test conditions. In Part I the 2nd-order stimulus is an amplitude modulated Gabor patch and the comparison (1st-order) stimulus is a conventional Gabor patch. In Part II uncorrelated noise is used to access the 2nd-order system, and the results are compared with those obtained using correlated noise.

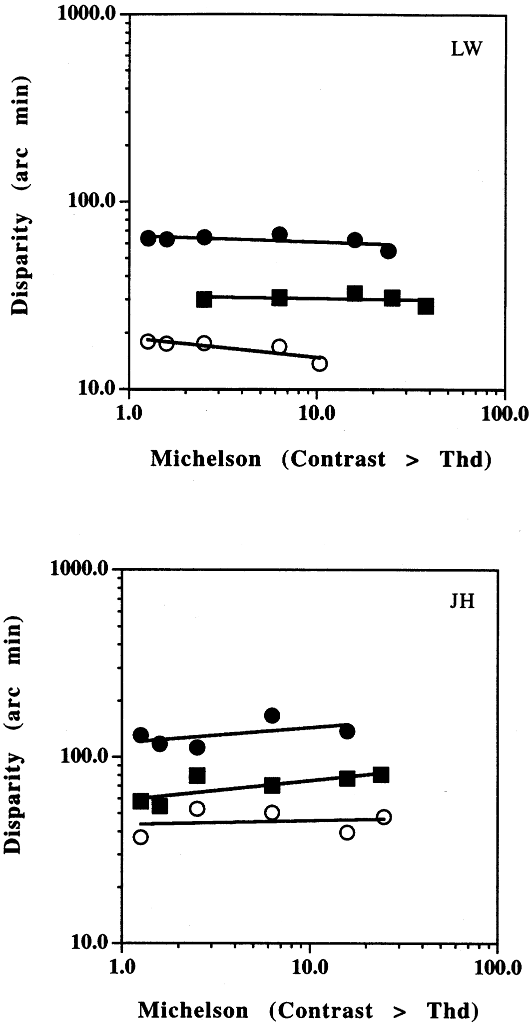

Fig. 2. The upper disparity limit ($D_{\max}$) is shown here for two subjects and three sizes ($\sigma = 11.5$ (○), 23 (■), and 46 (●), min at 1 m) as a function of Michelson contrast (relative to detection threshold). Standard error bars represent ± 1 S.E.M. and where invisible are smaller than the size of the symbol.

If it is true that the 2nd-order mechanism is not influenced by contrast to the same extent as the 1st-order mechanism, then we predict that the slope of the function representing the relationship between stereoacuity and contrast will be more shallow in the 2nd-order test conditions.

### *4.2. Part I: gabors versus AM patches*

#### *4.2.1. Stimuli*

In the first test condition we will assess stereoacuity for conventional and amplitude-modulated (AM) Gabor patches. The Gabor patches are identical to those described in Experiment 1 (Eq. (1)). The AM patches were created by multiplying a Gabor patch by a high frequency sinusoid (Fig. 1B). The grating components of the stimuli were oriented vertically, and the envelope was circularly symmetric in all test conditions reported here. The form of the AM function was:

$$L(x, y) = A \exp\left(\frac{-((x-x_0)^2+y^2)}{2\sigma^2}\right)[\sin(2\pi f_m(x-x_0))+1] \times \sin(2\pi f_c x + \phi) + L_0 \quad (3)$$

where $f_m$ represents the modulation frequency, $f_c$ represents the carrier frequency, $L_0$ is the mean luminance, and $\phi$ is a uniform random variable which is independently selected for each eye, on every trial, from the range (0, $2\pi$). $X_o$ represents the disparity offset which was in equal and opposite directions in each eye, and $A$ was chosen so that the Michelson contrast ($2A/L_0$) was 15 dB above the subjects' detection threshold for each condition. To ensure that the phase of the high frequency background carrier could not signal the position in depth of the amplitude modulation or contrast envelope, the absolute phase of this component was varied randomly and independently in each eye on every trial.

Fig. 3 illustrates schematically the Fourier power spectra of the components of the AM stimulus before (A) and after (B) multiplication We introduce disparity in this complex stimulus by shifting the modulation ($f_m$) and envelope positions in the two eyes. Note that in the final stimulus (B) there is no energy at the frequency of the modulation or the envelope. Therefore, in order to use the disparity information provided by these stimulus components it would be necessary to perform a non-linear operation such as rectification. Where there is energy in the Fourier transform (i.e. near or at the carrier frequency ($f_c$)) the output of bandpass linear filters will be uncorrelated in the two

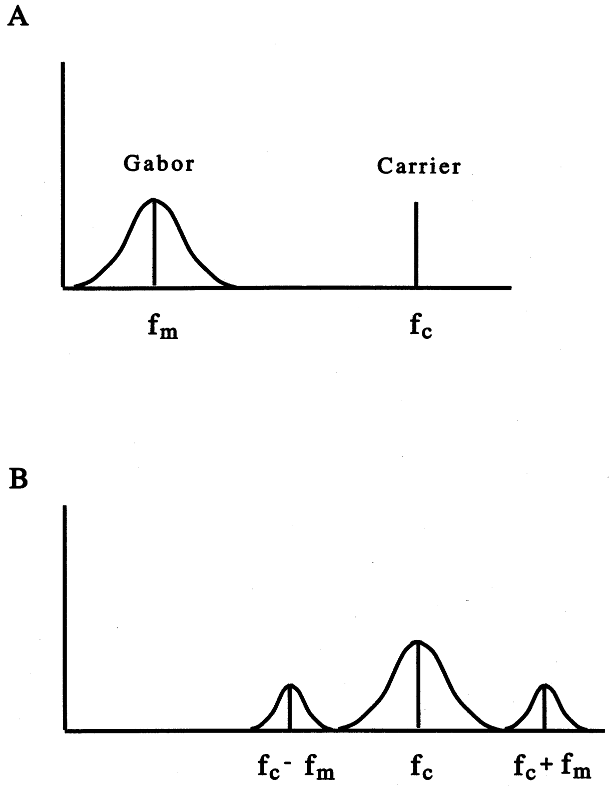

Fig. 3. A schematic illustration of the Fourier Power spectrum of the amplitude-modulated stimulus. The Gabor patch and high frequency sinusoid are represented in (A) prior to multiplication, and in (B) following multiplication. In this diagram $f_m$ represents the modulation frequency, and $f_c$ the carrier frequency. Note that there is no information present following multiplication (in the AM stimulus) at the spatial frequency of the modulation ($f_m$).

eyes because the phase of the carrier is randomized on each presentation.

Assuming that 1st-order stereopsis involves comparison of the output of bandpass linear filters, this stimulus will provide a random (and therefore irrelevant) disparity signal to a mechanism processing 1st order information. It will, however, provide two consistent disparity signals to a mechanism processing 2nd order information, one at the scale of the envelope and the other at the scale of the contrast modulation. In a recent publication we have shown that stereoacuity for such stimuli depends on the coarse-scale contrast envelope [15].

### *4.3. Results and discussion*

For these results and those of the following experiments, we fit the contrast-dependence data (plotted on log–log co-ordinates) with power functions; the slopes of these functions and their $r^2$ values are reported alongside the associated data on the graphs. The effect of contrast on stereoacuity for Gabor stimuli and AM patches is shown in Fig. 4, for two subjects. Results for two different carrier frequencies for the Gabor stimulus have been included to show that the difference in slope is not restricted to a specific spatial frequency. Furthermore, these two frequencies bracket the modulation frequency of the AM stimulus showing that the difference between the two sets of results cannot be attributed to the spatial frequency difference. For both subjects, contrast had a much weaker effect on performance for the AM stimuli than for the Gabor stimuli.

This observation is quantified by the slopes of the best-fitting power functions. The slopes of the functions obtained for Gabor patches of 1.31 (■) and 2.62 cpd (●), and for the AM stimulus (○) were −0.63, −0.70, −0.16 (LW) and −0.67, −0.544, −0.21 (JH), respectively. Not only were similar slopes obtained for both

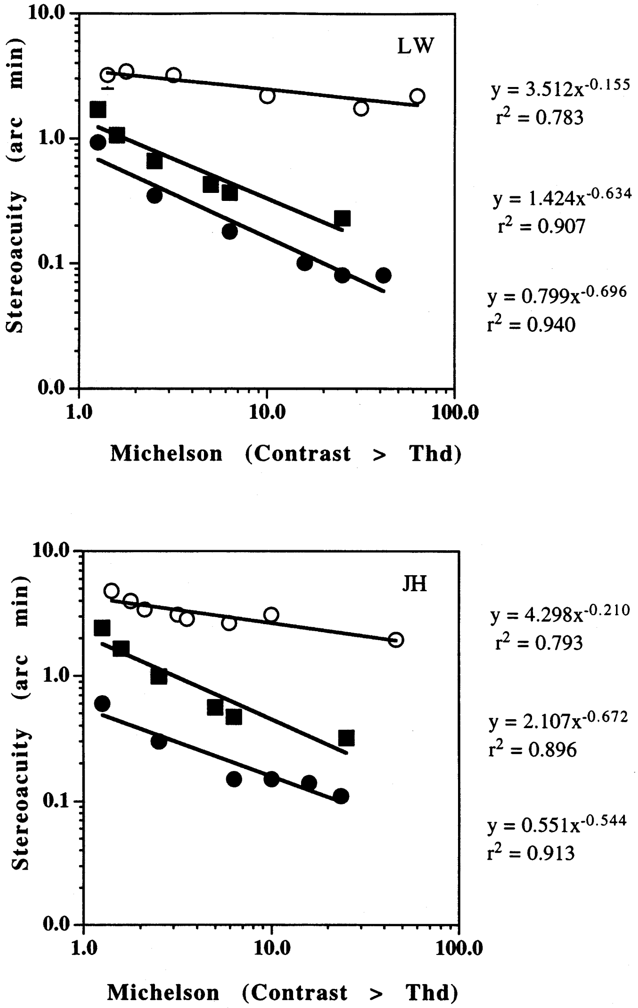

Fig. 4. Stereoacuity is shown here for Gabor (■,●) and AM (○) stimuli for two subjects as a function of Michelson contrast (relative to detection threshold). The modulation frequency of the AM stimulus was 1.64 cpd which was bracketed by the centre spatial frequencies of 1.31 cpd (squares) and 2.62 cpd (circles) of the Gabor patches. All stimuli had a $\sigma = 0.38°$ and the AM carrier grating was 6.4 cpd at 1 m. The solid lines represent the best fitting power functions; the corresponding slopes and $r^2$ values are shown to the right. Standard error bars represent ± 1 S.E.M.

Gabor conditions, but for both subjects these slopes were significantly higher than the slopes obtained for the AM stimulus.

### *4.4. Part II: correlated and uncorrelated noise patches*

#### *4.4.1. Stimuli*

We next assessed stereoacuity using patches of one dimensional, band-limited, spatial noise. The noise was vertically oriented and multiplied by a 2-D Gaussian envelope (Fig. 1C). The patches were generated using a commercially available image processing package (‘HIPS’). To create the noise pattern a random number generator was used to select one of 256 grey-levels for each line of the image. This noise pattern was then filtered (convolved with) a Gabor function (Eq. (2)). The Gabor used to filter the patches was relatively broad-bandwidth (1.89 octaves[4]) with a centre frequency of 1.5 cd and $\sigma = 0.22°$ at 1m. In the final stage of processing, the patches were multiplied spatially by a broad two-dimensional Gaussian window with a standard deviation of 0.57°.

It is essential to the validity of this experiment that the independently generated noise patches be uncorrelated. While the use of a random number generator to assign luminance values to each pixel should ensure that each patch is uncorrelated, we confirmed this by cross-correlating each of the individual images and averaging across the output images. We compared the averaged cross-correlation output with the results of a cross-correlation of two identical patches (autocorrelation). The peak of the autocorrelation function was 1.0 and the peak of the normalized averaged cross-correlation distribution was 0.00397. Thus the independently-generated noise patches are, for all practical purposes, uncorrelated.

These stimuli were presented either as correlated (same patch to each eye), or uncorrelated (randomly selected patches presented to each eye) stereo-pairs. In both instances the disparity was introduced by shifting the whole stimulus, both the noise and the Gaussian envelope. We have demonstrated previously that the correlated presentations activate mechanisms processing 1st-order information, while the uncorrelated stereo-pairs require 2nd-order processing [14].

### *4.5. Results and discussion*

Stereoacuity for correlated noise patches is more strongly influenced by stimulus contrast than is stereoacuity for uncorrelated noise patches. The results displayed in Fig. 5 show that this is consistent for both subjects.

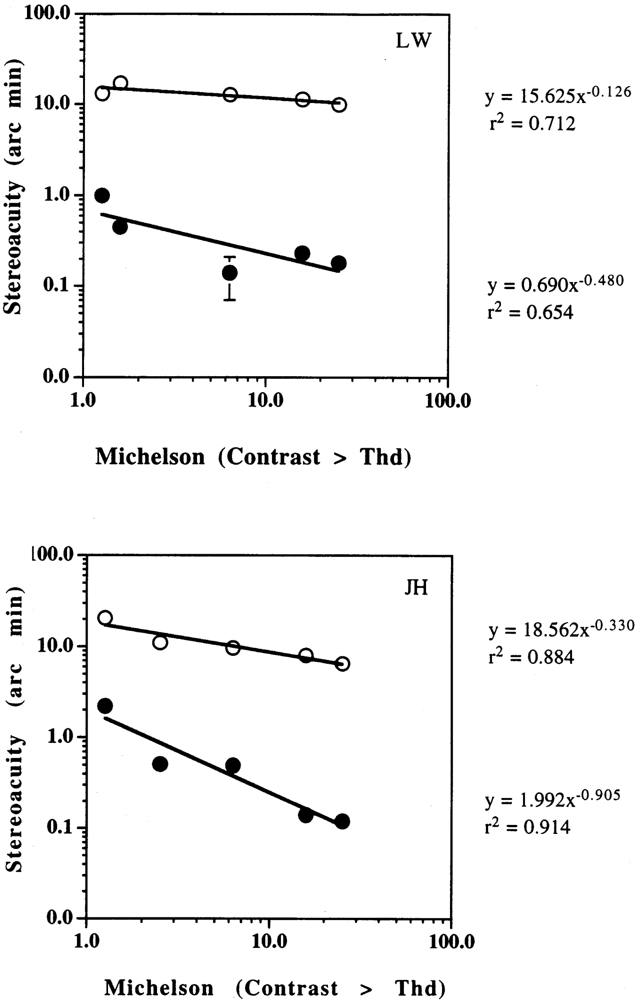

Fig. 5. Stereoacuity is shown here for correlated (●) and uncorrelated (○) noise stimuli for two subjects as a function of Michelson contrast. The centre frequency of the noise was 1.5 cd and $\sigma = 0.57°$ at 1 m. The solid lines represent the best fitting power functions; the corresponding slopes and $r^2$ values are shown to the right. Standard error bars represent ± 1 S.E.M.

The slopes of the best-fitting power functions for correlated (●) and uncorrelated noise (○) are $-0.91$, $-0.33$ (JH) and $-0.48$, $-0.13$ (LW), respectively. Once again, the slopes are higher when the 1st-order system is able to mediate performance, and more shallow when the 2nd-order system is needed to extract the stimulus envelope.

## 5. Experiment 3: stereoacuity as a function of interocular contrast ratio

In their original experiments Halpern and Blake [1] and Legge and Gu [2] both assessed the effect of interocular contrast differences on stereoacuity thresholds. Their data was consistent in demonstrating that dichoptic contrast changes were more debilitating

---

[4] The octave bandwidth was calculated using the Gaussian’s half-height and full width [27].

than binocular contrast variation (for 1st-order stimuli). Given the general immunity of 2nd-order stereopsis to substantial contrast variation, it seemed likely that their results would not be applicable to 2nd-order test conditions. To verify this, we measured stereoacuity for 1st- (Gabor) and 2nd-order (uncorrelated noise) stimuli for a range of interocular contrast ratios. The two stimuli had the same $\sigma$ (0.57° at 1m) and similar centre frequencies of 1.5 (noise) and 1.7 (Gabor) cd. In this study, the contrast of one eye (the preferred eye) was held constant at 0.5 Michelson, while the contrast ratio in the other eye was varied from 0.2 (large difference) to 1 (no difference). The results are shown in Fig. 6.

The thresholds measured using 1st-order stimuli replicate the results reported by Halpern and Blake [1] and Legge and Gu [2]. That is, performance is constant for contrast ratios up to approximately 0.5 and then quickly degrades. The slopes of the best-fitting power functions are similar to those reported previously at $-1.3$ (KF) and $-0.97$ (LW) (●). The 2nd-order results are similar for contrast ratios less than 0.5, but do not exhibit the same drop at high ratios resulting in relatively shallow slopes of $-0.28$ (KF) and $-0.47$ (LW) (○).

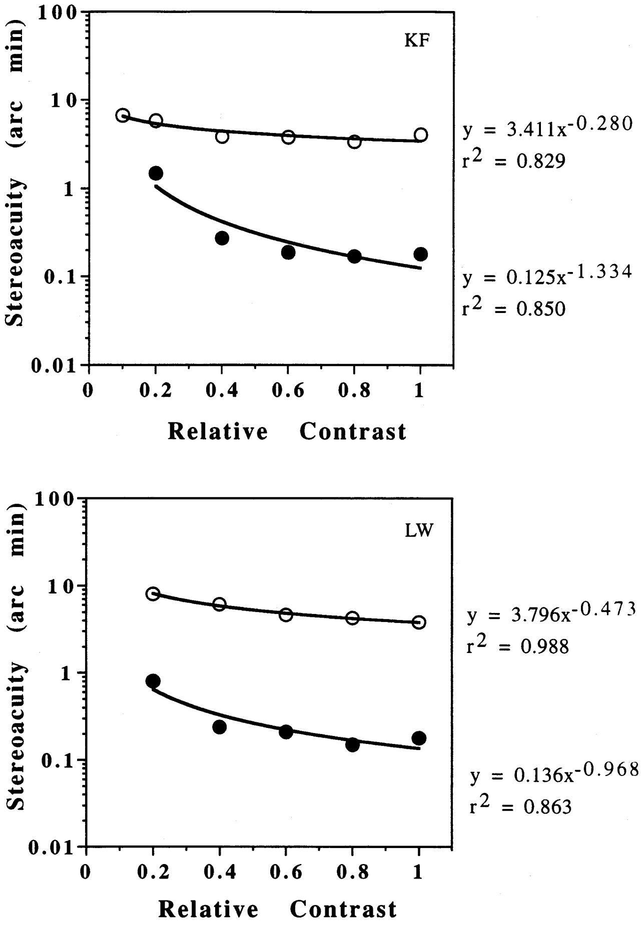

Fig. 6. Stereoacuity is shown here for 2nd-order (uncorrelated noise ○) and 1st-order (Gabor-●) stimuli for two subjects as a function of the interocular contrast ratio. The noise parameters are equivalent to those used in the preceding experiment, the Gabor patches had a centre frequency of 1.7 cd and $\sigma = 0.57$. The stimulus in the preferred eye was fixed at an intermediate Michelson contrast of 0.5. The $x$-axis plots the relative amount of contrast in the variable contrast eye. For example, at 1.0 both eyes receive a Michelson contrast of 0.5, while at 0.2 one eye receives 0.5 and the other 0.1. The solid lines represent the best fitting power functions; the corresponding slopes and $r^2$ values are shown to the right. Standard error bars represent ± 1 S.E.M.

## 6. General discussion

Comparison of the slope values for 1st- and 2nd-order stereopsis in the preceding experiments shows a consistent difference between the two, across stimuli and tasks. When 1st-order processing is used stereoacuity improves with increasing contrast with a cross-condition average slope of $-0.71$ for JH and $-0.65$ for LW. When performance is mediated by the envelope-based 2nd-order system, slopes are consistently shallower with an average of $-0.15$ for JH and of $-0.12$ for LW. Comparison of the effects of varying the interocular contrast ratio on 1st- and 2nd-order stereoacuity show a similar trend. That is, the 2nd-order slopes are invariably shallower indicating a greater resilience to interocular stimulus differences. This difference in sensitivity to contrast differences reinforces the notion that 2nd-order processing can be thought of as a form of 'back-up' to 1st-order stereopsis [15]. For example, when the 1st-order signal is unreliable as is the case for diplopic images (say of objects that lie outside Panum's fusion zone) the 2nd-order system is used to provide a coarse but reliable depth estimate. Similarly, in the results shown above, when the 1st-order disparity signal is degraded by interocular differences in contrast the visual system can use the disparity information provided via 2nd-order processing to assign a depth value to the stimulus.

While it is generally accepted that 1st-order stereopsis displays a strong dependence on stimulus contrast (with slopes on log–log plots near $-0.5$), the reason for this is not well understood. Halpern and Blake [1] suggest that it may be due to the statistics of the feature localization stage. They point out that the relatively shallow slope is consistent with the operation of a contrast non-linearity which occurs after monocular spatial filtering. This general feature-based explanation is supported by the data and modelling of Legge and Gu [2] who go one step further in identifying peaks in the luminance distribution as the likely features (in preference to centroids or zero-crossings).

How does the 1st/2nd-order distinction made here fit into this class of models? To begin, no one has yet implemented a model of stereopsis that explicitly computes and uses a 2nd-order disparity signal. It has been posited that models of stereopsis should follow existing models of 1st and 2nd-order motion [23,24] in that there is an initial (shared) filtering stage followed by rectification and another filtering stage in the 2nd-order pathway. If this form of model was applicable, then we would expect the dependence on contrast to be similar for both 1st- and 2nd-order stereopsis. The results presented here are therefore not consistent with this model, unless the rectification stage injects an independent source of noise of a multiplicative rather than additive kind. At this point we are not able to distinguish between this and the simpler explanation that 1st- and 2nd-order processing occur along separate pathways governed by different constraints.

### *6.1. Monocular localization and 2nd-order stereopsis*

In recent experiments [14] we have shown that when using 2nd-order stereopsis to make depth judgements, performance is identical to monocular localization of the same enveloped 1-D noise patch.[5] However, under conventional conditions (with the same noise stimulus in each eye) when the 1st-order mode is used, performance is improved by a factor of 10. In another set of conditions we separately assessed the effects of stimulus size and blur on stereoacuity and monocular localization using a range of stimulus types [19]. Here again we found that the 2nd-order results were different from the 1st-order data but were very similar to those obtained for monocular localization. These results support the proposal that the operations used to extract the stimulus envelope are performed along monocular pathways when in the 2nd-order mode of processing, and might be the same as those used to make monocular localization judgements for non-abutting targets. If the same non-linear operations are used to extract the stimulus envelope for 2nd-order stereoacuity as for monocular localization, then 2nd-order stereopsis should exhibit the same dependence on stimulus contrast. Hess and Holliday [25] have shown that monocular localization for stimuli similar to those used here, exhibits a shallow dependence on stimulus contrast (a fourth root law) not unlike that reported here for 2nd-order stereopsis. This was attributed to the type of multiplicative contrast noise known to be present in visual cortical neurones [26]. However, one might predict that given the prevalence of multiplicative noise in cortical (V1) neurons the 1st- and 2nd-order stereoscopic conditions should have both exhibited a shallow contrast dependence. Instead, the difference in slope values points towards the contribution of an additional noise input to 2nd-order processing that does not influence the 1st-order disparity signal. As it stands, the precise nature and location of this multiplicative noise remains unknown.

## Acknowledgements

This work was supported by the Medical Research Council of Canada (#MT 10818 to RH) and by Natural Sciences and Engineering Research Council of Canada (LW).

## References

[1] Halpern DL, Blake RR. How contrast affects stereoacuity. Perception 1988;17:483–95.

[2] Legge GE, Gu Y. Stereopsis and contrast. Vis Res 1989;29:989–1004.

[3] Cormack LK, Stevenson SB, Landers DL. Interactions of spatial frequency and unequal monocular contrasts in stereopsis. Perception 1997;26:1121–36.

[4] Julesz B. Foundations of Cyclopean Perception. Chicago IL: University of Chicago Press, 1971.

[5] Julesz B, Miller JE. Independent spatial frequency-tuned channels in binocular fusion and rivalry. Perception 1975;4:125–43.

[6] Schor CM, Wood I. Disparity range for local stereopsis as a function of luminance spatial frequency. Vis Res 1983;23:1649–54.

[7] Badcock DR, Schor CM. Depth-increment detection function for individual spatial channels. J Opt Soc Am A 1985;2:1211–5.

[8] Smallman HS, MacLeod DIA. Size-disparity correlation in stereopsis at contrast threshold. J Opt Soc Am A 1994;11:2169–83.

[9] Liu L, Tyler CW, Schor CM, Ramachandran VS. Positional disparity is more efficient in encoding depth than phase disparity. Invest Ophthalmol Vis Sci (Suppl) 1992;33:1373.

[10] Sato T, Nishida S. Second-order depth perception with texture-defined random-dot stereograms. Invest Ophthalmol Vis Sci (Suppl) 1993;34:1438.

[11] Sato T, Nishida S. Does an envelope-detecting mechanism mediate stereopsis for band-limited stimuli? Invest Ophthalmol Vis Sci (Suppl) 1994;35:1916.

[12] Wilcox LM, Hess RF. Linear and non-linear contributions to stereopsis. Invest Ophthalmol Vis Sci (Suppl) 1993;34:1187.

[13] Wilcox LM, Hess RF. $D_{max}$ for stereopsis depends on size, not spatial frequency content. Vis Res 1995;36:391–9.

[14] Wilcox LM, Hess RF. Is the site of non-linear filtering in stereopsis before or after binocular combination? Vis Res 1996;36:391–9.

[15] Wilcox LM, Hess RF. Scale selection for 2nd-order (non-linear) stereopsis. Vis Res 1997;37:2981–92.

[16] Hess RF, Wilcox LM. Linear and non-linear contributions to stereopsis. Vis Res 1994;34:2431–8.

[17] Lin L, Wilson H. Invest Ophthalmol Vis Sci (Suppl) 1995;36:364.

[18] Kovács I, Fehér A. Non-Fourier information in bandpass noise patterns. Vis Res 1997;37:1167–77.

[19] Wilcox LM, Elder JH, Hess RF. The effect of stimulus blur and size on stereoacuity. Invest Ophthalmol Vis Sci (Suppl) 1996;37:684.

[20] Statham A, Georgeson M. Stereo depth perception uses first-order phase and second-order position disparities. European Conference on Visual Perception, Helsinki, 1997.

---

[5] Monocular localization in these experiments was assessed in the same manner as Toet et al. [29] and Hess and Holliday [25], with non-abutting targets to ensure that there are no additional position cues available to aid alignment.

[21] Richards W. Anomalous stereoscopic depth perception. J Opt Soc Am 1971;61:410–4.

[22] Landers DD, Cormack LK. Some spatio-temporal interactions in stereopsis. Invest Ophthalmol Vis Sci (Suppl) 1997;38:907.

[23] Lin L, Wilson H. Stereoscopic integration of Fourier and non-Fourier patterns. Invest Opthmal Vis Sci (Suppl) 1995;36:364.

[24] Fleet DJ, Wagner H, Heeger DJ. Neural encoding of binocular disparity: energy models, position shifts and phase shifts. Vis Res 1996;36:1839–58.

[25] Hess RF, Holliday I. The coding of spatial position by the human visual system: effects of spatial scale and contrast. Vis Res 1992;32:1085–97.

[26] Tolhurst DJ, Movshon JA, Thompson ID. The dependence of response amplitude and variance of cat visual cortical neurones on stimulus contrast. Exp Brain Res 1981;41:414–9.

[27] Graham N. Visual Pattern Analyzers Oxford Psychology Series No. 16. New York: Oxford University Press, 1989.

[28] Simmons D, Kingdom FAA. Contrast thresholds for stereoscopic depth identification with isoluminant and isochromatic stimuli. Vis Res 1994;34:2971–82.

[29] Toet A, von Eekhout MP, Simons HL, Koenderink JJ. Scale invariant features of differential spatial displacement discrimination. Vis Res 1987;27:441–52.