Pergamon

PII: S0042-6989(97)00061-8

Vision Res., Vol. 37, No. 21, pp. 2981–2992, 1997

Printed in Great Britain
0042-6989/97 $17.00 + 0.00

Scale Selection for Second-order (Non-linear) Stereopsis*

LAURIE M. WILCOX,† ROBERT F. HESS‡

Received 4 June 1996; in revised form 26 August 1996; in final form 27 November 1996

In addition to the conventional luminance spatial frequency-dependent, disparity processing mode, there is a second-order luminance spatial frequency-independent type of processing available to the stereoscopic system. Here we use gaussian-enveloped, amplitude-modulated grating patches to determine how the stereoscopic system responds to the presence of two sources of second-order disparity information at different scales when there is no disparity information available via the conventional luminance-based system. In the first experiment we show that the stereoscopic system uses the disparity signal provided by the stimulus envelope, even though it is at a coarser scale than that provided by the amplitude modulation (AM). We then demonstrate that if the stimulus envelope is degraded via blurring, or if it is fixed at zero disparity, then performance depends on the finer-scale AM disparity signal. To show that the stereoscopic system uses the disparity signal provided by the AM we extend the carrier grating outside the borders of the AM stimulus, thereby making the boundary of the patch less discernible. Results obtained using this stimulus suggest that when two sources of second-order disparity information are present within the same stimulus (i.e., with no reliable luminance-based disparity signal available), the disparity signal provided by the coarser-scale contrast envelope vetoes the finer-scale disparity signal. The coarse-scale disparity information dominates as long at it provides an adequate disparity signal. When it is degraded, however, the finer-scale signal takes precedence. © 1997 Elsevier Science Ltd

Scale Stereoacuity Linear Non-linear First-order Second-order

GENERAL INTRODUCTION

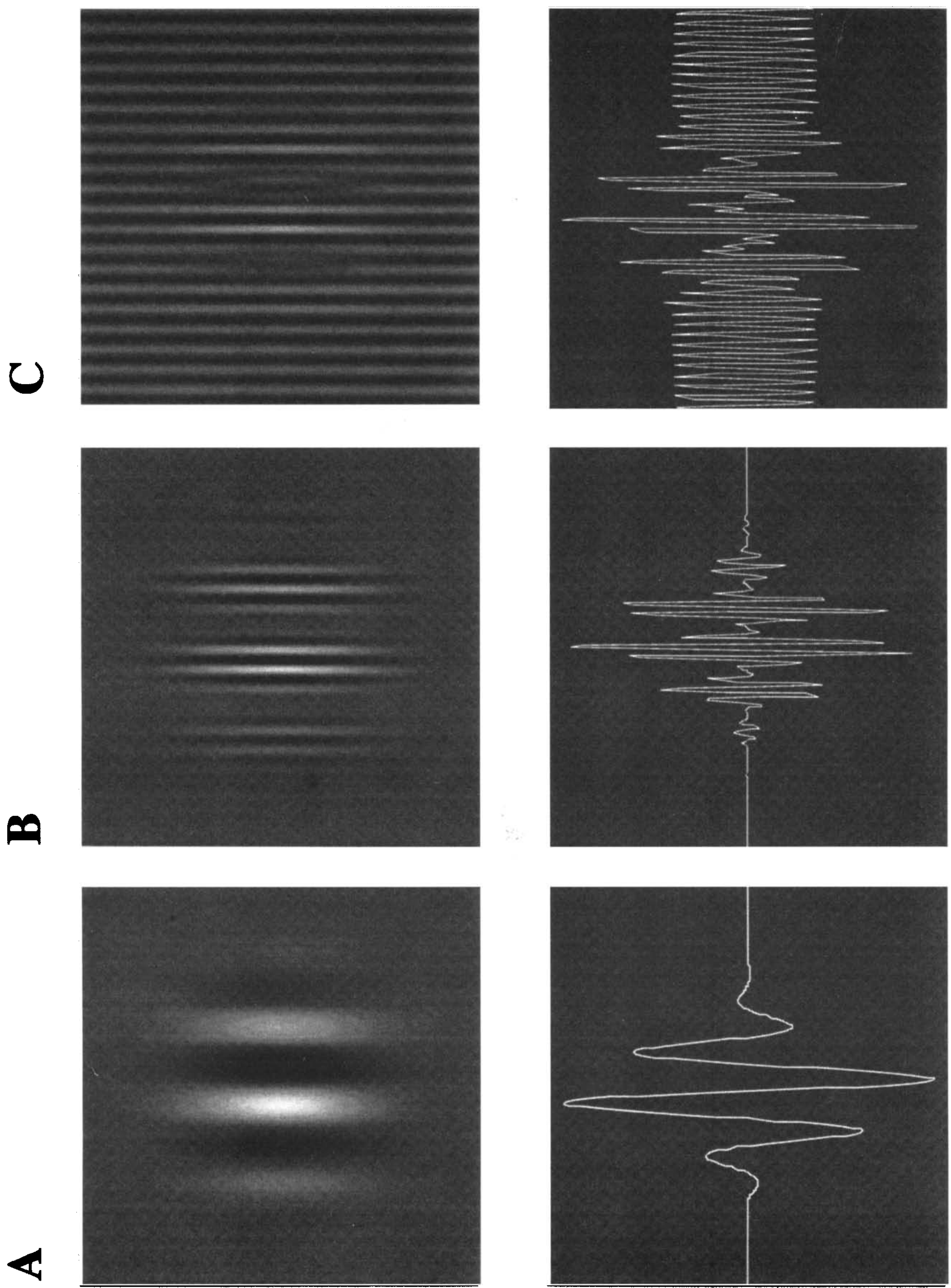
The stereoscopic system is not restricted to extracting a disparity signal from the output of linear luminance spatial frequency-tuned filters. While there is convincing evidence that such processing does indeed occur (among others: Julesz, 1971; Julesz & Miller, 1975; Schor & Wood, 1983; Schor *et al.*, 1984; Badcock & Schor, 1985; Smallman & MacLeod, 1994), this is not the only source of disparity information available to the stereoscopic system. A number of recent studies (Liu *et al.*, 1992; Sato & Nishida, 1993; Sato & Nishida, 1994; Fleet & Langley, 1994; Hess & Wilcox, 1994, Wilcox & Hess, 1995; Lin & Wilson, 1995; Kovács & Fehér, 1996; Wilcox & Hess, 1996) have reported evidence of a second mode of processing which is insensitive to changes in local luminance spatial frequency content. Instead, when this mode of processing is used, stereoacuity depends strongly on changes in the attributes of the contrast envelope, or boundary of the stimulus (see Hess & Wilcox, 1994; Wilcox & Hess, 1995; Wilcox *et al.*, 1996).

We have previously conducted a number of experiments to clarify the stimulus parameters and test conditions necessary to invoke one mode of processing over the other. For example, when stereoacuity was measured using Gabor stimuli, if there were less than four cycles of the carrier sinusoid visible within the gaussian envelope, performance depended on the luminance spatial frequency of the carrier (first-order processing). However, if there were more than four cycles visible then performance did not depend on the centre spatial frequency, but on the scale of the gaussian envelope (second-order processing) (Hess & Wilcox, 1994). The picture is less complicated for the upper disparity limit or D_{max}, which was determined solely by second-order processing. That is, when the stereo-pairs were diplopic the only disparity information used by the stereoscopic system was that present in the stimulus envelope; the luminance spatial frequency content was irrelevant (Wilcox & Hess, 1995). This result has recently been confirmed and extended by Kovács & Fehér (1996) using random-dot patterns. In another set of experiments we

*Portions of this work were presented at the Association for Research in Vision and Ophthalmology, 1995.

†To whom all correspondence should be addressed at: Department of Psychology, York University, 4700 Keele St., North York, Ontario M3J 1P3, Canada.

‡McGill Vision Research, McGill University, Montréal, Quebec, Canada.


A
B
C

used uncorrelated noise patches which had been windowed with a 2-D gaussian envelope to measure second-order stereoacuity (Wilcox & Hess, 1996). Although there was no disparity information available via luminance spatial frequency-dependent mechanisms, subjects could reliably see depth by way of the disparity information provided by non-linear operations which extract the contrast envelope.

Taken together, these and other experiments (Liu *et al.*, 1992; Sato & Nishida, 1993; 1994; Fleet & Langley, 1994; Lin & Wilson, 1995; Kovács & Fehér, 1996; Wilcox & Hess, 1996; Wilcox *et al.*, 1996) suggest that first- and second-order stereopsis are distinct and are used under specific stimulus conditions. The first-order mode is used when the stimuli are simple and there is little matching ambiguity. The second-order mode is used when presented with complex, detailed, stimuli that provide ambiguous interocular matches (e.g. narrow bandwidth Gabor patches), or when no reliable disparity signal is available via luminance spatial frequency-tuned receptive fields (e.g. uncorrelated noise patches, diplopic stereo-pairs). Further, Langley & Fleet (1996) have used adaptation/aftereffect procedures to demonstrate that second-order stereopsis is not simply based on an early distortion product which produces energy at the frequency of the contrast envelope.

There is convincing evidence that for conventional, first-order, stereopsis the optimal disparity for a given receptive field varies directly with its preferred luminance spatial frequency. Models such as those proposed by Marr & Poggio (1979), Ohzawa *et al.* (1990), and Jones & Malik (1992) are based on this assumption. Indeed, there are psychophysical data which support such an association (see Schor *et al.*, 1984; Smallman & MacLeod, 1994). These results suggest that, for first-order processing, fine stereoacuity is conveyed by fine-scale filters and coarse stereopsis by coarse-scale filters. A logical outcome of this organization is that for first-order stimuli, with luminance spatial frequency components separated by at least two octaves, stereoacuity will be determined by the finest scale filters responsive to the stimulus (see Howard & Rogers, 1995, Ch. 5.7).

One might expect that a similar rule would be applied to second-order stereopsis since, in principle, models of these two forms of processing (first- and second-order) need only differ in the addition of a rectification and subsequent filtering operations to the second-order pathway (e.g. Lin & Wilson, 1995). However, except for the observation that second-order processing, in general, seems to occur at larger scales, we do not know if it displays a similar preference for fine-scale filters.

In the following set of experiments we measure stereoacuity using a stimulus which provides no consistent disparity information via luminance-based, spatial frequency-dependent mechanisms. However, there are two sources of reliable disparity signals available via second-order processing: a coarse-scale envelope and a finer-scale modulation (for stimulus details see *Stimulus* section and Fig. 1). In our first set of experiments we separately vary the overall scale of the stimulus, the spatial frequency of the amplitude modulation, and the size of its envelope, to determine which of the two sources of disparity information is used by the stereoscopic system. In our second set of experiments we examine the dependence of stereopsis on the AM frequency when the patch boundary is blurred or when it provides no disparity signal. In our third set of experiments, we use a modified form of our original AM stimulus to assess the dependence of performance on the AM spatial frequency when the stimulus boundary is made less salient. The combined results are surprising for they show that the rules determining scale selection for first- and second-order stereopsis are markedly different.

GENERAL METHODS

Subjects and apparatus

For each experiment extensive measurements were obtained using two experienced subjects. A third, inexperienced subject participated in Experiment 3. All Subjects had stereopsis within normal ranges (Randot Stereotest) 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.

Calibration

Since we claim that our stimulus does not provide any reliable disparity signal for luminance-based spatial frequency-dependent mechanisms it was important to ensure that our equipment and method of stimulus generation were linear. Single luminance measurements of spatially uniform fields do not provide an adequate test of the linearity of a system. Instead, we verified the linearity of our equipment using the stimulus that we subsequently used in our experiments. We drifted the gaussian-enveloped amplitude-modulated sinewave past a narrow slit and measured the luminance at each pixel, averaged over 10 repetitions, using a UDT photometer. To determine if there was significant energy at any spatial frequency components other than those predicted by

FIGURE 1 *(opposite)*. The stimuli used in the experiments reported here are illustrated in the top row along with their luminance profiles in the second row: (A) Gabor patch; (B) gaussian-windowed, amplitude-modulated sinewave (AM stimulus); and (C) a modified version of (B), in which the sinewave carrier function is visible outside the edges of the gaussian envelope. Note that the examples shown here are for illustration and are not representative of the range of conditions tested; for example, in the case of the AM stimulus the side peaks were typically closer to the centre band.

Fourier analysis of the stimulus we did the following: we plotted the power spectrum of the measurements for our stimulus for different modulation frequencies and positions on the screen. We then calculated the amount of energy present in frequencies other than those expected. In all instances these values were very small, with the largest being 1% of the total stimulus energy, while for the remaining conditions this value was closer to 0.5%.

Stereoscopic depth was achieved using "Display Tech" liquid crystal shutters mounted in trial frames.* 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 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, by the amount required for each test condition.

Stimulus

The stimuli used in Experiments 1 and 2 were gaussian-enveloped amplitude-modulated sinewaves [see Fig. 1(B) and equation (1)]. This stimulus was a product of three components: (1) a gaussian envelope; (2) a modulation factor; and (3) a high spatial frequency carrier sinusoid. The modulation factor was the sum of two terms: (1) a low frequency sinusoid; and (2) a pedestal. The pedestal term was included in the modulation factor to ensure that when the low frequency sinusoid (modulation) was eliminated a high spatial frequency Gabor patch remained. This permitted examination of the contribution of the carrier grating to depth judgements in the absence of the modulation component. To be certain that the high frequency carrier grating provided no information concerning the direction of the depth displacement of the modulation grating we randomly and independently varied the absolute phase of the carrier grating in each eye, and on every trial.

In Experiment 3 a modified version of this stimulus was used. As shown in equation (2), only the modulation sinusoid was multiplied by the gaussian envelope; the addition of the pedestal ensured that the high frequency modulation grating was visible outside the boundaries of the stimulus envelope. Consequently, apart from the visibility of the stimulus boundary, the two stimuli were essentially the same [Fig. 1(C)].

The grating components of the stimuli were oriented vertically, and the envelope was circularly symmetric in all test conditions reported here. The following equations represent the amplitude modulated patch [equation (1)] and the modified version where the background sinusoid is visible [equation (2)]:

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

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

where f_m represents the modulation frequency, f_c represents the carrier frequency, L_0 is the mean luminance, and ϕ is a uniform random variable which is independently selected for each eye, on every trial, from the range [0, 2π]. x_0 represents the disparity offset which was in equal and opposite directions in each eye, and A was chosen so that the Michelson contrast ($\frac{2A}{L_0}$) was 15 dB above the subjects' detection threshold for each condition. The size and spatial frequency of the patch were manipulated by changing the viewing distance to

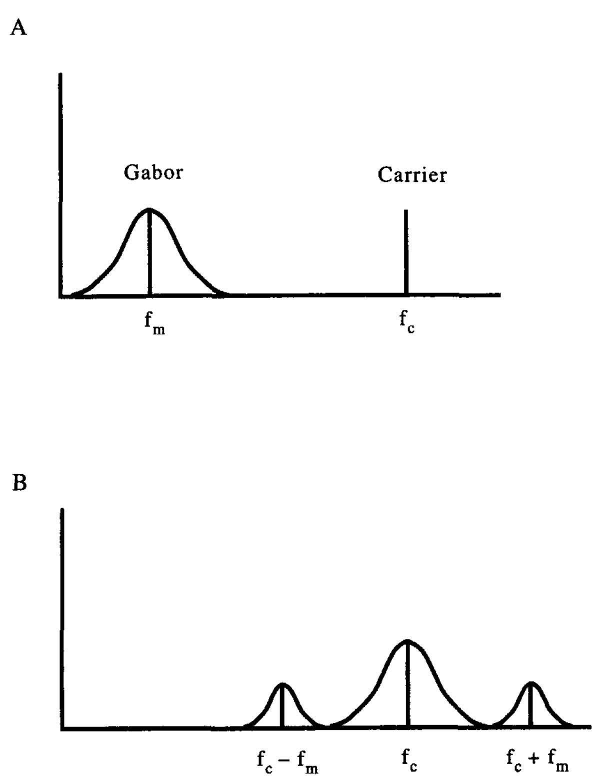


FIGURE 2. A schematic illustration of the Fourier power spectrum of the amplitude-modulated stimulus. The Gabor patch and high frequency sinusoid are represented in (A) prior to multiplication; and in (B) following multiplication. In this diagram f_m represents the modulation frequency, and f_c the carrier frequency. Note that there is no information present following multiplication (in the AM stimulus) at the spatial frequency of the modulation (f_m).

*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. We have avoided this problem by using a display with a single, fast phosphor and by ensuring that the stimulus contrasts used in our experiments were well below the threshold for detection of the cross-talk.

the screen, or by changing the appropriate parameters in the equation used to generate the AM stimuli.

Figure 2 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 eyes because of the phase randomization of the carrier grating. Assuming that first-order stereopsis involves comparison of the output of bandpass linear filters, this stimulus will provide a random (and for Experiments 1 and 2, irrelevant) disparity signal via first-order processing. It will, however, provide two consistent disparity signals via second-order processing, one at the scale of the envelope and the other at the scale of the contrast modulation.

The period of the background carrier sinusoid was fixed at four lines per cycle which corresponds to 6.5 c/deg at 1 m, and is the smallest period that can be used to adequately represent the waveform. Control experiments showed that, within a reasonable range of test values, there was no effect of manipulating the frequency of the carrier grating on stereoacuity. This is to be expected given that (for all experiments) the absolute phase of the carrier grating was varied randomly and independently in each eye, and on every trial.

Procedure

In all experiments reported here we measured the accuracy with which a single AM stimulus could be localized in depth relative to two identical peripheral patches which formed the fixation plane. The two reference stimuli were located directly above and below the stereo-target at a separation of at least 4 σ. In Experiments 1 and 2, when large gaussian envelope sizes were used ($\sigma > 1.0$ deg), a single reference patch was used. In control experiments we found that this manipulation did not affect stereoacuity for envelope sizes of $\sigma = 0.38$ and 0.60 deg.

Stereoacuity was measured using the method of constant stimuli, and a set of 11 test values. The range of test values 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 of" to "behind" the peripheral patches. Sub-pixel spatial accuracy was achieved by recomputing the location of a stimulus and the stimuli were presented within a temporal raised cosine of total duration of 1 sec; stimuli were visible for approximately 0.3 sec. 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:

$$P(x) = A(0.5 + 0.5\,ERF((x - B)/(\sqrt{2}C))) \quad (3)$$

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 is the measure of stereoacuity, as it increases stereoacuity deteriorates. Each datum represents the average of at least three such estimates from which the standard error of the mean was derived.

With the exception of Experiment 3, when the modified AM stimulus was used, contrast thresholds were measured prior to testing for all conditions. Subsequently, the test contrast was set at 15 dB above threshold a value which, in preliminary trials, provided a reasonable range of test contrasts. We used the method of adjustment with a randomized starting point to obtain seven binocular threshold estimates, which were then averaged. When assessing contrast thresholds, the contrast of the composite stimulus was varied, and subjects indicated the point at which it was just detectable. Contrast thresholds varied across stimulus conditions but, on average, thresholds were close to 6% (Michelson) resulting in a test contrast of approximately 31%.

In Experiment 3 we found that thresholds for detection of the AM superimposed on the visible background grating were very high, and varied little with modulation spatial frequency. Therefore, we used a fixed contrast of 80% throughout this set of experiments. To verify that the use of this high contrast did not introduce an artefact, the dependence on modulation frequency was reassessed for one subject using a contrast of 30% and is depicted as the dashed line in Fig. 9. It is clear from these data that the contrast used had no effect on the pattern of results.* Contrast was controlled by varying a (14 bit) voltage from the digital signal generator and multiplying it by the Gabor stimuli output from graphics memory, the contrast of which could also be scaled (8 bit resolution).

EXPERIMENT 1—STEREOACUITY FOR AM STIMULI

Introduction

We have created a stimulus (see *Stimulus* section) which will provide no consistent disparity signal via luminance-based spatial frequency-selective mechanisms. However, there are two sources of disparity information which can be made available through second-order processing. A non-linear operation, such

*Previous examinations of the contrast dependence of stereopsis have activated first-order processing, and have reported approximately a negative square-root dependence (Legge & Gu, 1989; Halpern & Blake, 1988). To the contrary, we have observed in this and previous studies that there is very *little* dependence of second-order stereopsis on contrast (Wilcox & Hess, 1997).

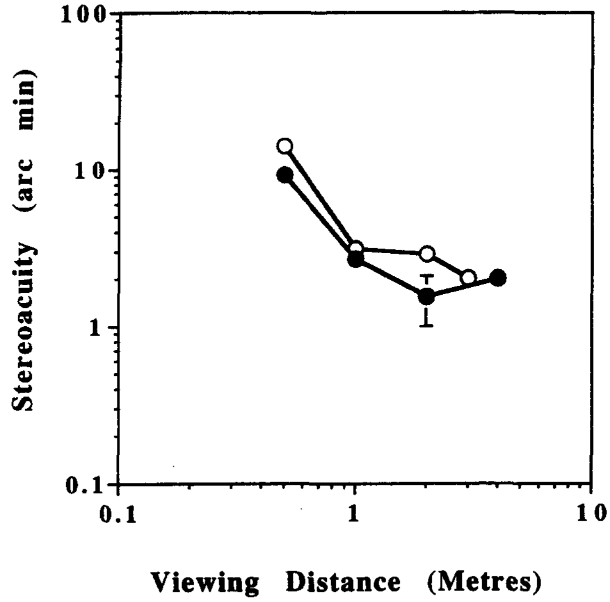


FIGURE 3. Stereoacuity was initially measured for AM stimuli at a range of viewing distances for two subjects, LW (●) and JH (○). Subject LW was tested at an additional viewing distance of 4 m. The resulting patch sizes and spatial frequencies were as follows: $\sigma = 0.76$–0.13 deg (0.09 deg for LW), modulation frequency = 0.8–5.0 c/deg (6.5 for LW), carrier frequency = 3.3–19.6 c/deg (26.0 for LW). Error bars represent ±1 SEM, and where invisible, are less than the size of the symbol.

as rectification, will produce a disparity signal which can be used to represent the contrast envelope of the stimulus, and one which can be used to represent the amplitude modulation (AM) within that envelope. If we can extrapolate from what we know about conventional stereoscopic processing, we would expect that to make precise stereoacuity judgements, the stereoscopic system would use a fine scale disparity signal to optimally represent the small disparity offsets. Thus, we predict that when we measure stereoacuity separately as a function of size and AM frequency, performance will depend on the frequency of the AM, but not on the overall size of the gaussian envelope.

Results

Initially, we measured the effect of scale on stereoacuity thresholds for AM stimuli. Subjects were tested at viewing distances ranging from 0.5 to 3.0 m (LW was also tested at 4 m) with constant physical patch parameters, resulting in the following range of sizes and spatial frequencies $\sigma = 0.76$–0.13 deg, modulation frequency = 0.8–5.0 c/deg, carrier frequency = 3.3–19.6 c/deg. Figure 3 shows stereoacuity performance for both subjects as a function of viewing distance.

The results were very similar for the two subjects. At large scales stereoacuity was poor, and improved as scale decreased up to a modulation frequency of approximately 1.5 c/deg and an envelope size of $\sigma = 0.38$ deg, at which point the curves flattened. Of course, when we changed the scale of the stimulus, both the size of the patch and the spatial frequency of the modulation varied. Thus, either of these variables could be responsible for the changes in stereoacuity; in the following test conditions we examined the separate effect of these two variables. Figure 4 depicts the effect of varying the modulation frequency while the envelope size was held constant ($\sigma = 0.38$ deg), for a fixed carrier frequency (6.5 c/deg).

We were surprised to find that there was little effect of modulation frequency on stereoacuity for this stimulus. Clearly performance does not improve with increasing modulation frequency, on the contrary, performance is slightly worse at the highest modulation frequency. It seems unlikely that the decrease in stereoacuity with increasing scale (Fig. 3) is due to the concomitant change in modulation frequency. Instead, when we varied the size of the stimulus envelope, and held the modulation (1.64 c/deg) and carrier (6.5 c/deg) frequencies constant, there was a clear decrease in performance with increased envelope size (see Fig. 5) which could well be responsible for the effect of scale shown in Fig. 3.

Discussion

Depth judgements made using these AM stimuli have revealed that second-order stereopsis is not sensitive to contrast modulation of the interior of the stimulus. If such stimuli were rectified, disparity information should be provided at the frequency of both the envelope and the amplitude modulation. Except for the lowest AM frequencies, the spatial scale of the envelope is lower than that of the AM, therefore the stereoscopic system should be able to obtain a more precise depth estimate from the AM signal. Surprisingly, in spite of this, the stereoscopic system uses the disparity signal provided by the envelope of the patch. Were it not for the fact that there is evidence that AM frequency modulation can support stereopsis (Carney & Shadlen, 1984), it would be

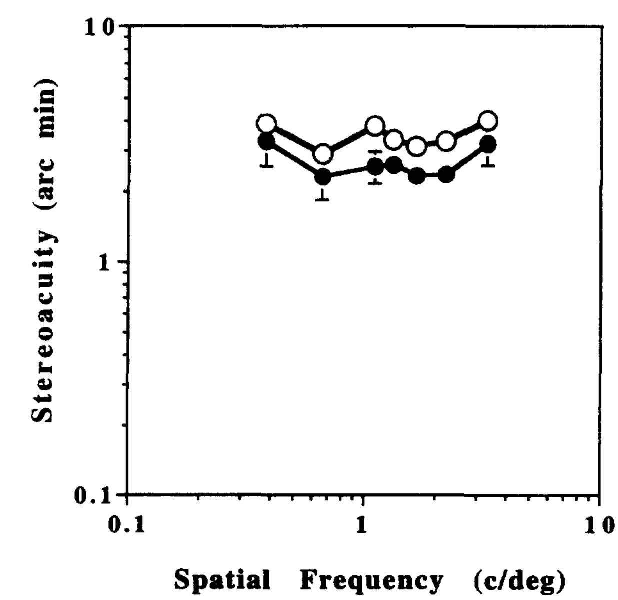


FIGURE 4. Stereoacuity was measured for AM stimuli as a function of the modulation spatial frequency for two subjects, LW (●) and JH (○). The envelope size and carrier spatial frequency were held constant at $\sigma = 0.38$ deg and 6.5 c/deg, respectively. Error bars represent ± 1 SEM, and where invisible, are less than the size of the symbol.

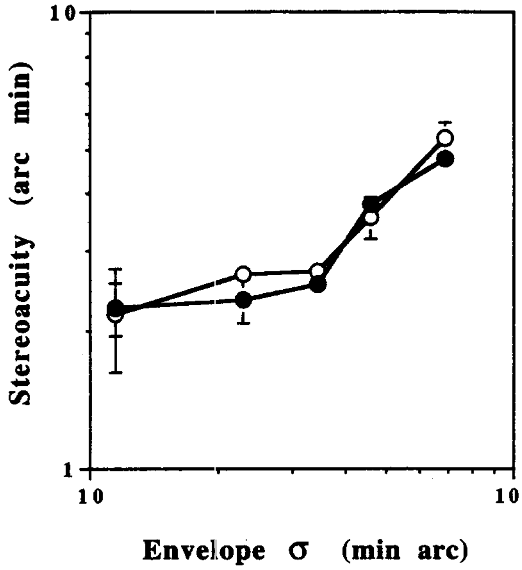


FIGURE 5. Stereoacuity is shown here as a function of envelope size for the AM stimuli and two subjects, LW (●) and JH (○). The modulation (1.64 c/deg) and carrier (6.5 c/deg) frequencies were held constant. Error bars represent ± 1 SEM, and where invisible, are less than the size of the symbol.

tempting to conclude that there is no multi-scale representation after rectification for second-order stereopsis. Instead, it seems that processing of the coarser scale envelope has precedence over that of the finer scale AM modulation for the second-order mode. In the next experiment we manipulate the quality of the coarse-scale disparity signal to test the hypothesis that the fine-scale, AM disparity signal can be used by the visual system when the coarse-scale information is degraded, or absent.

EXPERIMENT 2—STEREOACUITY WITH A DEGRADED ENVELOPE-BASED DISPARITY SIGNAL

Introduction

The results of Experiment 1 suggest that, in the presence of an envelope-based disparity signal, stereoscopic performance is not dependent upon the frequency of AM of our stimuli. This finding seems to be at odds with that reported by Carney & Shadlen (1984). However, there is an important difference between our stimulus and that of Carney and Shadlen; their stimulus was not windowed, but filled the viewing area. Thus, in their study disparity information was available for second-order processing at one scale only. Therefore, an explanation for the discrepant results is that when disparity information is present both at the overall patch scale and the AM frequency scale, only the former is used for second-order processing. If, as in Carney and Shadlen's experiment, there is no coarse-scale disparity signal, then the second-order processing mode will extract a disparity signal from the finer-scale AM. To test this hypothesis, we measured stereoacuity under conditions where the envelope disparity signal was (1) less salient; and (2) absent.

Methods and results

The same subjects, apparatus, methodology and stimuli described in Experiment 1 were used here. Note that, as in Experiment 1, the absolute phase of the carrier grating was varied randomly in each eye, on each trial. Two conditions were tested: in the first the envelope size was increased so that it extended to approximately 2 deg in the periphery. This increase in size resulted in not only a more peripheral patch edge (and thus more neurally blurred) but also a physically more blurred edge, thereby degrading the envelope's disparity signal (see Wilcox *et al.*, 1996). In the second condition the disparity of the envelope was fixed at zero while the disparity of the contrast modulation was varied. Stereoacuity was measured as in Experiment 1 with the method of constant stimuli. For the large stimuli there was room on the display for only one reference stimulus, but this modification did not affect performance (see *Methods*). In the first condition, stereoacuity was measured for two AM spatial frequencies (0.44 and 3.3 c/deg for LW; 0.5 and 2.1 c/deg for JH) while the patch size (σ = 1 deg) and carrier frequency (6.5 c/deg) were held constant. The results for two subjects are illustrated in Fig. 6.

When the gaussian envelope was large, performance shows a clear dependence on the AM frequency that was not present when the envelope was smaller and provided a more reliable disparity signal. Similarly, we observed a dependence on AM frequency when the envelope disparity was fixed at zero. Figure 7 displays the results for two subjects for a range of envelope sizes (JH σ = 0.57 and 0.95 deg; LW σ = 0.38, 0.95 and 1.5 deg).

Discussion

The results of Experiment 2 are very different from

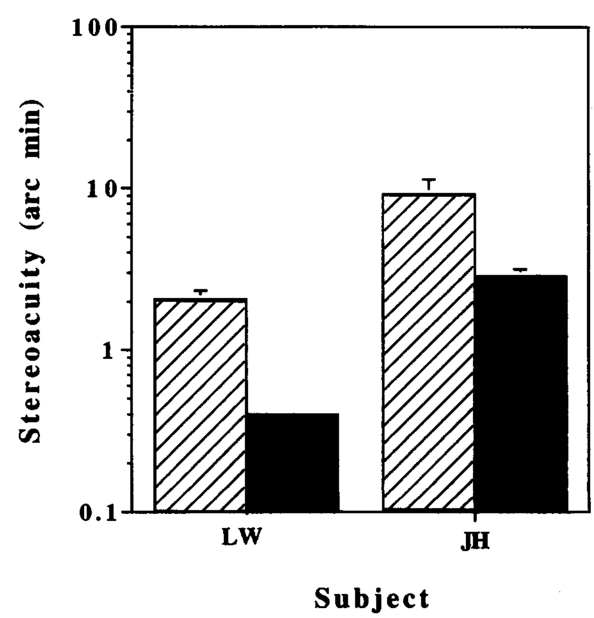
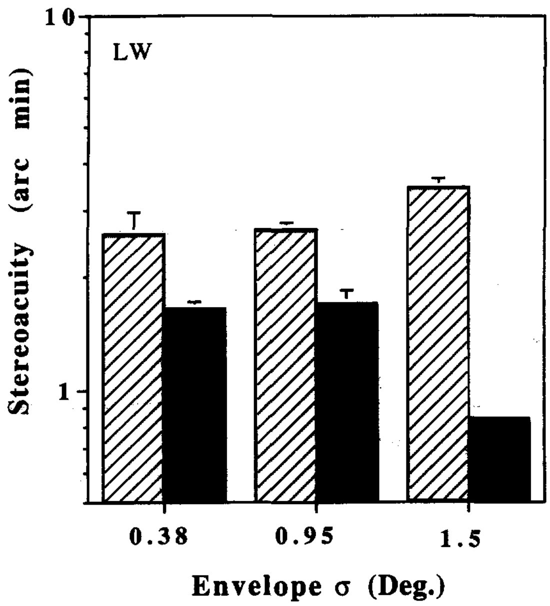


FIGURE 6. In the second experiment, large AM stimuli (σ = 1 deg) were used to measure stereoacuity for two subjects at spatial frequencies of 0.44 (LW) and 0.5 c/deg (JH) (light grey bars) and 3.3 (LW) and 2.1 c/deg (JH) (dark grey bars). Error bars represent 1 SEM.



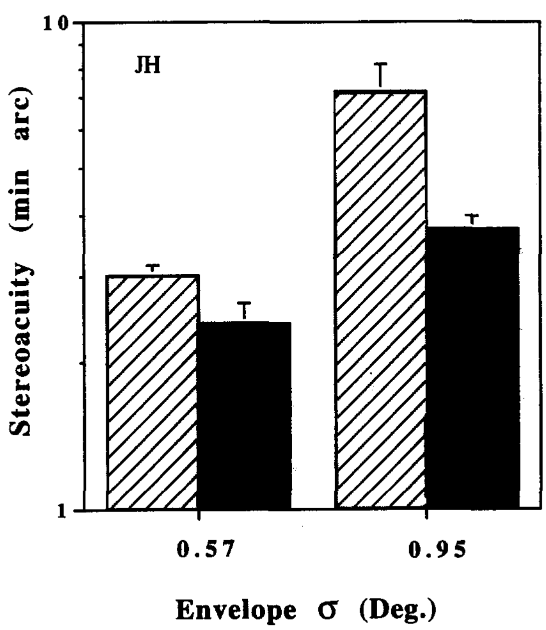


FIGURE 7. Stereoacuity was measured using AM stimuli. In all test conditions the envelope was fixed at zero disparity while the disparity of the modulation varied according to the method of constant stimuli protocol. The light and dark grey bars represent low (0.44 c/deg) and high (2.63 c/deg) spatial frequencies, respectively. Data are shown here for two subjects at a range of envelope sizes (JH $\sigma = 0.57$ and 0.95 deg; LW $\sigma = 0.38$, 0.95 and 1.5 deg). Error bars represent 1 SEM.

those obtained when we varied AM modulation frequency in Experiment 1. In both test conditions we observed a clear dependence on the AM frequency that was not evident in the first experiment. Thus, it seems that by simply degrading the envelope disparity signal we are able to influence the scale at which the stereoscopic system is operating. These data account for the apparent discrepancy between the results of Experiments 1 and those of Carney & Shadlen (1984). That is, for second-order stereopsis their grating stimulus had disparity information at a single scale, that of the AM. Because there was no coarser-scale disparity information available to the second-order system, stereopsis depended upon the AM frequency.

We would like to comment here that although the stereo-thresholds are comparable with those obtained in previous conditions, the task was perceived to be difficult in the condition where the envelope was fixed at zero disparity (Fig. 7). Subject LW found that for small envelope sizes it was sometimes difficult to perceive depth, and subject JH could not do the task at the smallest envelope size ($\sigma = 0.38$ deg). One explanation for this difficulty is that in this condition the envelope boundary is sharp, and so provides a very strong zero disparity depth signal. The strength of the envelope-based disparity signal could interfere with the non-zero AM disparity signal, making depth difficult to perceive. In spite of this problem, both subjects were able to make reliable depth judgements for the remaining test conditions, and in all of these there was a clear effect of AM frequency on performance.

Judging by the results presented in Figs 6 and 7, and those of Carney & Shadlen (1984), the stereoscopic system is able to extract a reliable disparity signal from the AM. However, it has a preference for the coarse-scale contrast envelope disparity signal and seems to use the finer-scale information only when a poor localization signal is provided by the overall stimulus.

EXPERIMENT 3—STEREOACUITY FOR MODIFIED AM STIMULI

Introduction

The results of Experiments 1 and 2 show that the stereoscopic system *can* use the disparity provided by an AM signal, but only when the stimulus boundary information is degraded. In the previous experiment we achieved this by blurring the stimulus envelope both physically and neurally. In the next experiment we ask if we can induce the stereoscopic system to use the AM disparity signal without modifying the physical characteristics of the patch boundary. To this end, we made the AM stimulus boundary difficult to discern by modifying our stimulus equation so that the high spatial frequency background grating extended outside the envelope boundary and was visible over the whole screen [see Fig. 1(C) and equation (2)].

Results and discussion

We measured stereoacuity using the methodology and apparatus described above, for this background-visible AM stimulus. We used a fixed high stimulus contrast, and measured stereoacuity for vertical carrier frequency (6.5 c/deg), four modulation frequencies (0.44–3.3 c/deg), and a fixed envelope scale ($\sigma = 0.38$ deg). For comparison, we also measured stereoacuity for our original background-invisible AM stimuli of the same size, contrast, and modulation frequencies. In all instances the phase of the carrier grating was independently and randomly varied for each eye, on every trial. The dependence of stereoacuity on modulation frequency

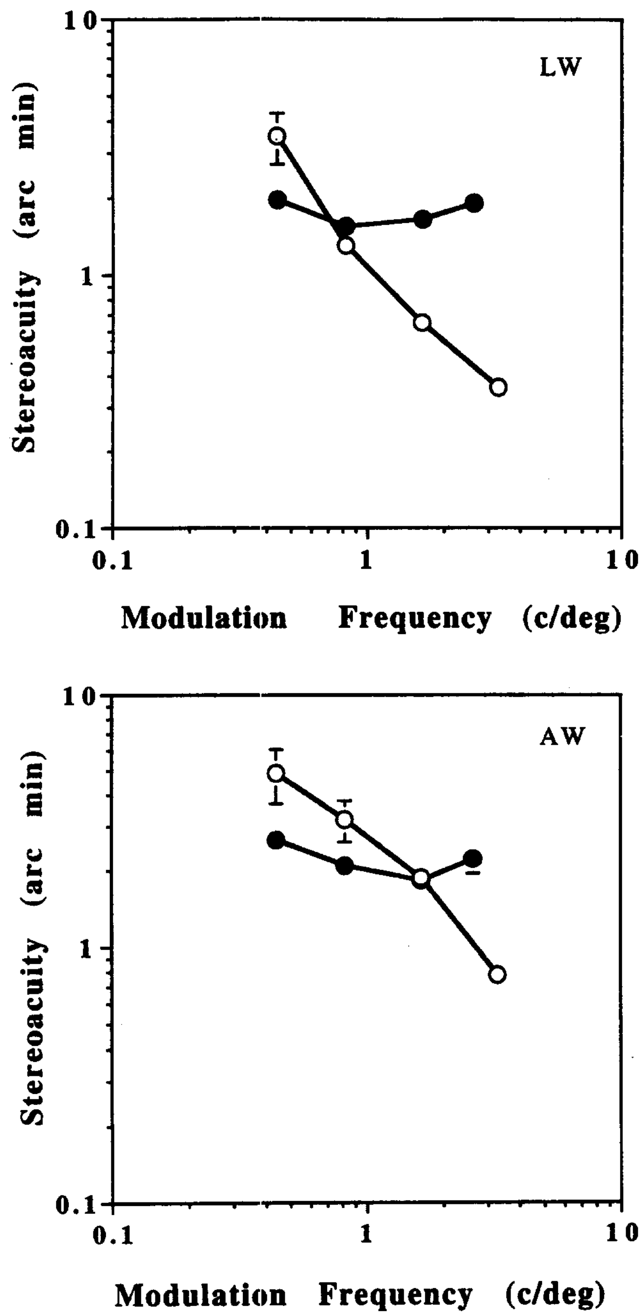


FIGURE 8. Stereoacuity is shown here for two subjects (LW and AW) as a function of modulation spatial frequency. Performance was assessed using the AM stimulus (●) and the modified AM stimulus (○), for which the carrier grating was visible outside the patch boundary. In both cases $\sigma = 0.38$ deg, the carrier frequency = 6.5 c/deg, and the contrast was fixed at 80%. Error bars represent ± 1 SEM, and where invisible, are less than the size of the symbol.

for both types of AM stimuli is shown in Fig. 8, for two subjects.

The results of this experiment confirm the predictions generated by Experiments 1 and 2. That is, when the boundary of the AM stimulus is not salient, stereoacuity depends on the spatial frequency of the AM modulation. Comparison of the two sets of results, AM stimuli with and without a visible background grating, illustrates the striking difference in the subjects' ability to perform this task. Note that this difference in ability is obtained even though the identical fine-scale disparity information is available in both conditions. Further, this comparison supports our argument that subjects are able to use the disparity information supplied at the fine scale of the AM, but that this information is ignored, or suppressed, when a coarse-scale disparity signal is available via the contrast envelope of the patch.

To further verify that, for this modified AM stimulus,

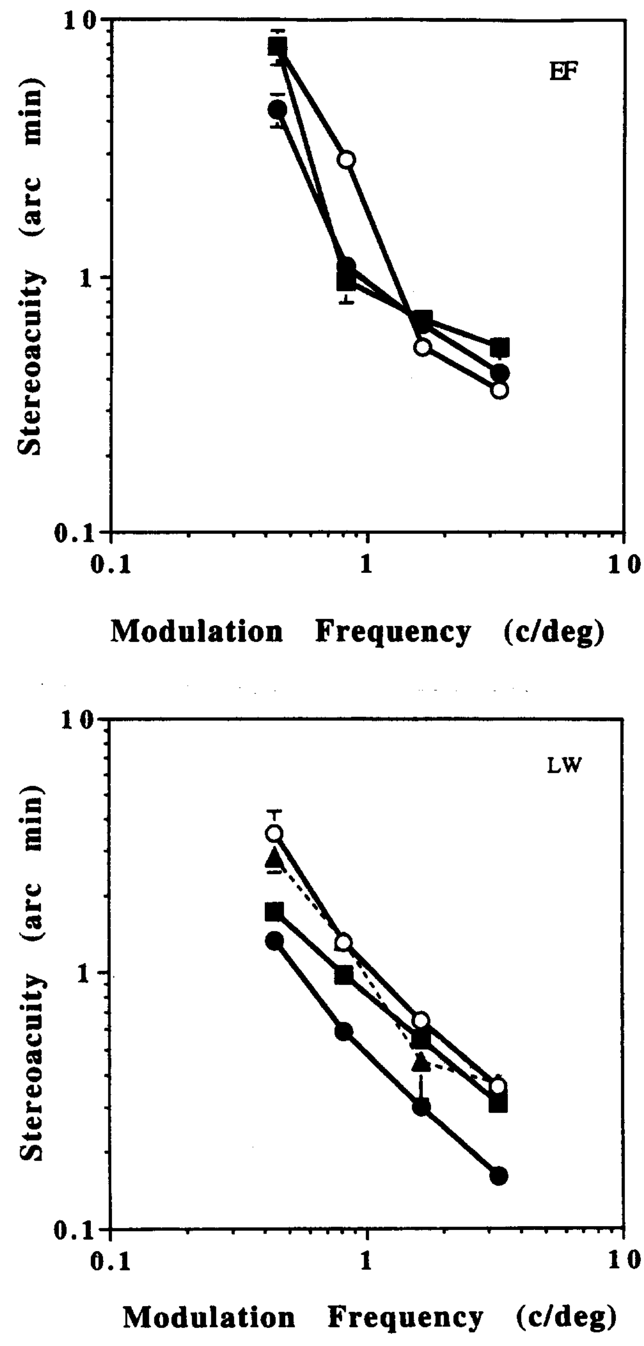


FIGURE 9. The dependence of stereoacuity on modulation frequency for the modified AM stimulus is plotted for two subjects (LW and EF). The three solid curves represent envelope sizes of $\sigma = 0.38$ (○), 0.76 (■), and 1.14 (●) deg. The data represented by the dashed curve and solid triangles (subject LW) were obtained under the same conditions ($\sigma = 0.5$ deg) except that the contrast was reduced to 30%. Error bars represent ± 1 SEM, and where invisible, are less than the size of the symbol.

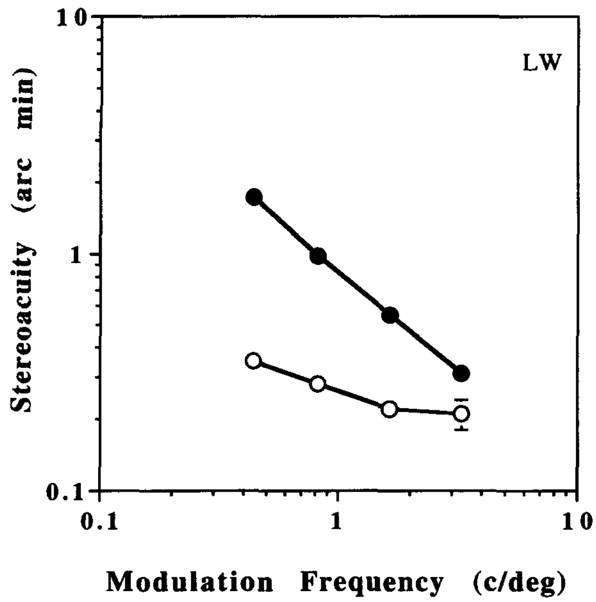


FIGURE 10. Stereoacuity was measured for one subject (LW) at a range of modulation frequencies using a conventional Gabor patch (○) and the modified AM stimulus (●). For both stimuli the contrast was fixed at 80% and $\sigma = 0.76$. Error bars represent ± 1 SEM, and where invisible, are less than the size of the symbol.

the disparity signal of the stimulus envelope is not used, we measured stereoacuity using this background visible AM stimulus for two subjects as a function of modulation frequency (0.44–3.3 c/deg) for three envelope sizes ($\sigma = 0.38$, 0.76, and 1.14 deg) with a fixed carrier frequency (6.5 c/deg). If the stimulus envelope was providing a disparity signal, we would expect performance to become poorer as the size was increased, as shown in Fig. 5. Figure 9 depicts the results obtained for two subjects (EF and LW).

As expected, both subjects show improved stereoacuity with increased modulation frequency, and neither of the subjects exhibit a decrease in performance with increased envelope size. On the contrary, LW shows the opposite pattern of results for stereoacuity improves as envelope size is increased. This pattern of results suggests that when the fine-scale modulation disparity signal is used, performance can be enhanced by increasing the number of cycles. EF, however, did not display this pattern; the difference between the two sets of results is probably due to the two subjects' experience in making depth judgements. Whereas LW was a highly experienced subject, EF had not previously participated in stereoacuity experiments.*

In Experiment 3, when the AM disparity signal was used to make stereoacuity judgements, all subjects reported that they did not use the reference patches to make their relative depth judgements. Instead, they were able to detect the disparity of the modulation relative to the carrier grating within the patch. Indeed, we found that stereoacuity was not affected when both reference patches were removed, leaving no zero-disparity reference plane. Given that the phase of the carrier grating was randomized in each eye on every trial this was a puzzling finding. One likely explanation is that subjects were able to adjust their vergence on each trial to fixate on depth plane defined by the carrier. Therefore, no depth offset was perceived in the carrier alone, and the position of the AM signal was determined relative to this fixation plane. We are confident that this vergence adjustment could provide no additional information about the direction of the depth offset of the AM or envelope components. However, it would add a small amount of disparity noise (maximum offset = 4.5 min for a carrier of 6.5 c/deg) which would be constant across all conditions tested.

Lin & Wilson (1995) also used a form of AM stimulus, a sixth spatial derivative of a gaussian (D6) multiplied by a 12 c/deg horizontal grating, to measure stereoacuity. They reported that it was possible to assess stereoacuity when this AM stimulus was presented stereoscopically and that stereoacuity depended on the modulation spatial frequency, with performance becoming better with increasing modulation frequency. However, for these D6 patterns the overall size and centre frequency are confounded. This means that in their experiment the improvement in performance that they attributed to the increased spatial frequency could equally have been attributed to the reduction in the size of the stimulus envelope. Although there are differences between their D6 stimulus and our modified AM stimuli (used in Experiment 3), the stimuli were similar in that the high-frequency carrier grating was visible outside the D6 boundary. Thus, the results of Experiment 3 are useful in interpreting their modulation frequency dependence data, and show that as Lin & Wilson (1995) had assumed, stereopsis for their stimulus may indeed have been mediated by the AM frequency and not the coarser-scale envelope.

In previous experiments, we have found that when stereoacuity is mediated by second-order processing, performance is approximately a factor of 10 worse than for first-order processing (Hess & Wilcox, 1994; Wilcox & Hess, 1996). However, Lin & Wilson (1995) reported that stereoacuity for their D6 AM stimulus was only a factor of 2 worse than obtained for conventional D6 stimuli. The improvement in relative performance under first- and second-order conditions in their experiments might well be due to the use of the finer-scale AM disparity signal. As shown in Fig. 9, performance improves markedly for high frequency AM. In a follow-up condition, we measured stereoacuity as a function of carrier frequency for conventional Gabor patches of the same size and contrast as the stimuli used in Experiment 3. A comparison of the two test conditions is provided in Fig. 10.

It is clear that the difference between stereoacuity measured in the first-order and (fine-scale) second-order

*EF's ability to use the disparity signal provided by the modulation frequency in spite of his inexperience is encouraging. His data confirm our assumption that the results of these experiments can be generalized, and do not simply apply to well practised, highly trained observers.

modes is contingent on the frequency of the AM. We note that, with these AM stimuli at an AM frequency of approximately 3 c/deg this difference is close to a factor of 2, the same as reported by Lin & Wilson (1995). However, our results suggest that to make a valid comparison of first- and second-order stereoacuity it is essential to consider the *scale* of the second-order disparity used to do the task.

GENERAL DISCUSSION

Unlike the first-order stereoscopic mode, which uses fine-scale disparity information to make high-resolution stereoacuity judgements, the second-order mode defaults to the lowest scale disparity information available in a stimulus (Experiment 1). However, the second-order mode can operate at a range of scales, and it will, if the quality of the disparity information derived from the coarse-scale contrast envelope of the stimulus is degraded. Under these conditions a clear dependence on the AM frequency is observed (Experiments 2 and 3). Such degradation can be achieved by either blurring the boundary of the stimulus neurally or physically, by setting its disparity to zero, or by rendering it perceptually less salient by having the carrier extend into the background.

Although the results seem counter-intuitive, the differences we have observed in scale selection between first- and second-order stereopsis do provide certain advantages to the stereoscopic system. The first-order mode may be well designed to detect disparity using the fine-scale texture across the surface of an object or scene, whereas the second-order mechanism may be well designed to discard texture information, in order to detect the global disparity of objects or surfaces. One possibility is that the second-order mode, in doing so, acts as a range-finder. That is, the coarse-scale disparity signal provided by the second-order mode serves to guide subsequent matches at finer scales within the first-order processing mode, thus reducing ambiguity and false matches. This proposal is appealing for it provides a potential functional role for the second-order mode, which is consistent with certain models of stereopsis which assume that processing of disparity information proceeds in a coarse-to-fine manner (Marr & Poggio, 1979; Wilson *et al.*, 1991).

If the preceding description is sound, then stereoacuity measured for stimuli which provide disparity information via both processing modes would always be accurate to the scale of the signal available via the first-order mode. We found that for Gabor patches performance depended upon the spatial frequency of the carrier grating (and so the first-order mode) if there were less than approximately four cycles of the carrier visible (Hess & Wilcox, 1994). However, for patches with more than four cycles, visible performance depended on the size of the gaussian envelope (and so the second-order mode). We interpreted these results to mean that the conventional first-order mode was used to process disparity information unless matching ambiguity was introduced by increasing the number of cycles within the patch. Under such conditions the coarse-scale, second-order signal was used to provide a depth estimate and stereoacuity was poor. This result is inconsistent with the range-finding proposal, for if the second-order mode were able to help the first-order mode by reducing ambiguity then performance should have remained stable (and quite good), irrespective of changes in the number of cycles present.

So, why does the second-order system default to the coarse-scale disparity signal? The answer to this question will undoubtedly be linked to the function that second-order stereopsis serves in human vision. One possibility is that the second-order mode serves as a back-up system to the high-resolution, first-order mode of processing. Results to this point support this conjecture, in that we have observed that first-order stereopsis has precedence over second-order, as long as it provides a reliable disparity signal. Under a variety of test conditions and stimulus parameters we have seen how the second-order mode of processing takes over for the first-order mode, for example, when the stereo-pairs consist of uncorrelated noise, complex patterns, or are diplopic.

There are a number of situations in which a second-order disparity signal could be very helpful. For example, typically much of the world lies outside Panum's fusional zone, and should be seen as diplopic. Certainly the conventional first-order processing would not be able to provide coarse depth estimates for such images, and so the second-order mode would provide a means of extending the range of perceived depth to disparity ranges outside Panum's fusional area. In addition, in the natural environment objects often have complex textured surfaces. Such surfaces may provide unreliable disparity signals via the luminance spatial frequency-based first-order processing, and it would be to the system's advantage to be able to use a more global disparity signal. In serving as a back-up system which is primarily concerned with crude estimates of relative depth, it makes sense that the second-order system would default to processing information at the coarse-scale of the object boundary to reduce matching ambiguity.

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Acknowledgements—We would like to thank James Elder for his insightful comments on early versions of the manuscript and Eric Fredericksen for many helpful discussions. This work was supported by the Medical Research Council of Canada (#MT 10818) and by the Natural Sciences and Engineering Research Council of Canada.