Linear and Non-Linear Filtering in Stereopsis

ROBERT F. HESS,* LAURIE M. WILCOX*

To better understand the spatial filtering operations underlying stereopsis, and their relationship to those underlying monocular localization of the same stimuli, we examined the dependence of stereoacuity on carrier and envelope size of Gabor patches. For stimuli of broad spatial bandwidth, stereoacuity depends on the carrier spatial frequency whereas for stimuli of narrow bandwidth, stereoacuity depends on the modulation frequency. The dependence of stereoacuity on the separation of the reference elements differs for stimuli of broad and narrow spatial frequency bandwidths. These relationships suggests that stereopsis has access to two different types of information from the early filters which we term, linear and non-linear. This distinction is important not only for understanding the relationship between monocular and stereoscopic localization, but also for understanding the different filter operations underlying stereopsis.

Stereopsis   Monocular localization   Linear   Non-linear

INTRODUCTION

A central issue in understanding the nature of stereoscopic processing is to clarify the relationship between monocular and stereoscopic localization. The simplest possible connection, namely that stereoscopic processing involves no more than a comparison of monocularly derived location information, which was proposed by Wheatstone (1838) and supported by the later experiments of Stratton (1990), has been refuted by a number of investigations (Berry, 1948; Stigmar, 1970; Foley, 1976; Westheimer & McKee, 1979; Schor & Badcock, 1985; McKee, Welch, Taylor & Bowne, 1990; McKee, Levi & Bowne, 1990). Stereoscopic sensitivity cannot be predicted from a knowledge of monocular localization of the same stimulus. Furthermore, the effects of a number of key variables such as spatial frequency, eccentricity and blur (Berry, 1948; Stigmar, 1971; Schor & Badcock, 1985) are different for stereopsis compared with corresponding monocular spatial localization. These differences between monocular and stereoscopic performance have led to the notion that while the initial peripheral processing of monocular and stereoscopic localization may be similar, the final localization stages are different. Although a number of studies have been concerned with the properties of the early linear filtering operations subserving stereopsis (among others, Yang & Blake, 1991; Frisby & Mayhew, 1978; Heckmann & Schor, 1989; Tyler & Barghout, 1992) there has been little attempt to relate the nature of the early filtering operations underlying stereoscopic and monocular localiz-

ation. In this study we explore the extent to which these two processes share a common initial spatial filtering stage and whether this stage is indeed linear.

An interesting aspect of foveal processing of monocular spatial information is that for non-abutting, band-limited elements, it is the size of the contrast envelope not the carrier frequency that determines performance (Toet, 1987; Toet, von Eekhout, Simons & Koenderink, 1987; Toet & Koenderink, 1988; Kooi, De Valois & Switkes, 1990; Burbeck, 1988; Hess & Holliday, 1992). This finding suggests that there is a non-linearity in the spatial filtering prior to the monocular localization stage which enables the contrast envelope to be extracted (see Hess & Holliday for one possible model). Similar models have also been proposed for motion and texture perception (Sperling & Chubb, 1989; Boulton & Baker, 1993). The purpose of this study is to investigate whether a similar non-linearity is evident in the early filtering for stereoscopic processing. If it is, it would strengthen the view that the initial filtering operations are similar for comparable stereoscopic and monocular spatial processing. Additionally, such a finding would establish that the more central stages of stereopsis have access to the outputs of non-linear as well as linear filters, a feature not present in existing models of stereopsis.

We use a three-Gabor alignment task where the middle Gabor is displaced in depth relative to the fixation plane which is defined by two peripheral Gabor patches. Monocularly, the task is identical to that used by Toet et al. (1987), Toet and Koenderink (1988), Kooi et al. (1991) and Hess and Holiday (1992) to investigate the non-linear properties of monocular spatial accuracy. The results suggest that stereoscopic processing can operate in one of two modes depending on the bandwidth of the stimuli. For narrow band stimuli, non-linear

*McGill Vision Research, Department of Ophthalmology, McGill University, Room H4-14, 687 Pine Avenue West, Montreal, Quebec, Canada H3A 1A1.

filtering operations underlie stereoscopic and monocular spatial judgements. For broadband stimuli, quite different filtering operations subserve the two types of processing. Furthermore, although the initial filtering operations appear to be the same for monocular and stereoscopic processing of stimuli that are spatial frequency narrowband, the levels of performance are very different. This suggests that there are differences in their more central localization stages.

METHODS

Subjects and apparatus

Extensive measurements were obtained using two experienced subjects. Both subjects had normal stereopsis (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. The mean luminance of the display was approx. 49 cd/m². Stereoscopic depth was achieved using 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 100 Hz per eye. The high frame rate was important in reducing binocular asynchrony, which in our case was 5 msec.

Stimuli

The stimuli were all patches of sinusoidal grating enveloped in both the x- and y-dimensions by a Gaussian envelope (see Fig. 1).

These stimuli are commonly referred to as "Gabor" patches. 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 Gabor functions was:

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

where A is the amplitude of the function, and σ is the standard deviation of the Gaussian envelope defining the patch. The choice of sinusoidal modulation at sine phase ensures that there is no mean luminance component in the stimulus at low numbers of cycles. The size and spatial frequency of the patch were manipulated by changing the viewing distance to the screen, or by changing the appropriate parameters in the equation used to generate the Gabor patches.

Two different stimulus arrangements were used for the reference stimulus. In one the reference stimuli were two identical Gabor stimuli as shown in Fig. 1(A). In the other, the reference stimulus was a sinusoidal bull's eye target of the same spatial periodicity as the central Gabor [Fig. 1(B)]. In each case, the distance between the target and reference stimulus was a constant fraction of
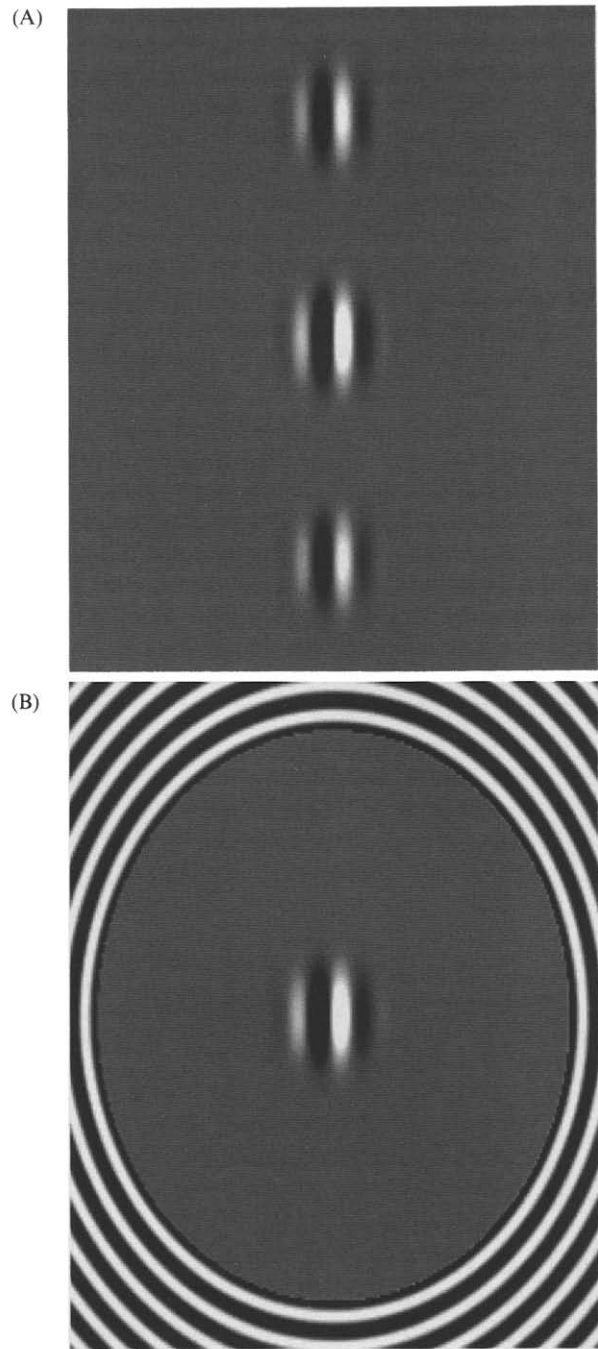
(A)
(B)

FIGURE 1. Shown here are the stimuli we used to measure stereoacuity. Three vertically oriented and aligned Gabor patches (see text for detailed description of stimuli) were presented simultaneously using a raised cosine temporal envelope of 1 sec duration. Thus the stimuli were visible for approx. 0.5 sec. Equal and opposite horizontal shifts in the left and right eyes made the central target appear in depth relative to the zero disparity reference plane which was defined either by (A) two identical Gabor patches or (B) a radial bulls-eye pattern which had the same spatial period and suprathreshold contrast as the target.

the size of the target's Gaussian envelope. The second method was adopted to extend the range of sizes for the target's Gaussian envelope. In both cases, contrast thresholds were measured for both the target and reference elements and they were presented at the same suprathreshold contrast level.

Procedure

We measured the accuracy with which a single Gabor patch 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 (Fig. 1). The boundaries of the screen and the other surrounding objects provided a rich peripheral fusion stimulus. The distance between the target and the reference patches was varied in the second experiment reported below. In all subsequent experiments this separation was held constant at 8 times the standard deviation of the Gaussian envelope (see text). Stereoacuity was measured using the method of constant stimuli, with a set of 11 stimuli covering a range of crossed and uncrossed disparities. This range was chosen individually for each stimulus condition to bracket the subject's stereo-threshold, or the point at which the perceived location of the central stimulus changed from being "in front" to "behind" the peripheral patches. 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 of 1 sec using a forced-choice (1IFC) technique. The observers' task was to identify on each trial whether the central target was positioned in front or behind the two outside stimuli; any one run involved eleven depth offsets, each 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:

$$P(x) = A(0.5 + 0.5*ERF((x - B)/(\sqrt{2.0}*C))) \quad (2)$$

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. Therefore, as the standard deviation parameter increases stereoacuity declines. Each datum represents the average of at least three such estimates from which the standard error of the mean was derived. It is well known that stereoacuity shows extensive practice effects (McKee & Westheimer, 1978). While it was not our aim to document these effects we did ensure that each subject had sufficient practice to reach asymptotic levels of performance.

Contrast detection thresholds were determine for the central stimulus alone and for the two peripheral stimuli concurrently (central fixation), for all conditions. The method of adjustment with a randomized starting point was used to obtain seven binocular threshold determinations which were averaged to provide the final estimate. Subsequently, the contrast of all three patches was set to be 8 (LMW) or 12 (JH) dB above their individual contrast thresholds. Contrast was controlled by varying a (14-bit) voltage from the digital signal generator and multiplying it with the Gabor stimuli output from graphics memory, the contrast of which could also be scaled (8-bit resolution). This technique provided accurate estimates of contrast threshold as the Joyce display screen has a linear Z-amplifier.

RESULTS

Since this investigation involves comparison of stereoacuity obtained using stimuli with different spatial properties, we first assessed the relationship between stereoacuity and both stimulus contrast and reference element separation. The relationship between stereoacuity and suprathreshold contrast is displayed in Figs 2 and 3 for two subjects (A and B) for stimuli of different spatial frequency bandwidths and centre frequencies (Fig. 2—0.18 octave bandwidth, SF = 2.62 and 5.24 c/deg; Fig. 3—1.13 octaves bandwidth, SF = 0.33, 0.66, 1.31, 2.62 and 5.24 c/deg).

For the spatially narrowband stimuli (Fig. 2), the expected square-root relationship (solid line) is seen over the full extent of the measurable contrast range (Halpern & Blake, 1988; Legge & Gu, 1989). For spatially broadband stimuli (Fig. 3), the relationship is similar; the solid line in Fig. 3 has a slope of −0.5 on these log–log coordinates and provides a reasonable
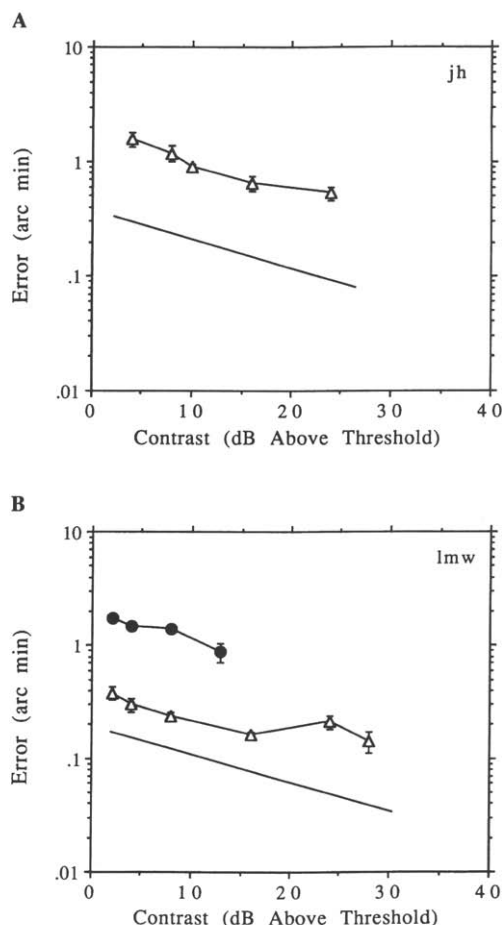

FIGURE 2. (A, B) Performance error is plotted here as a function of contrast (in dB above contrast threshold), for two subjects, and two spatial frequencies: 2.62 (●), and 5.24 (△) (σ = 68.7 and 34.4 min arc respectively). These Gabor patches had a narrow bandwidth (0.18 octaves). Error bars indicate ± 1 SEM and for comparison, the solid line without data points has a slope of −0.5.
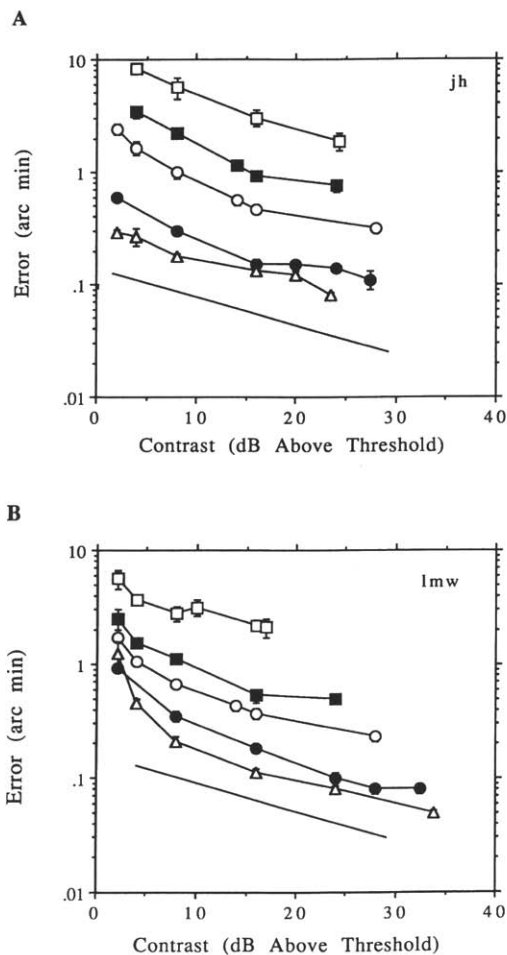
A

B

A

B

FIGURE 3. (A, B) As in Fig. 2(A, B), the effect of stimulus contrast on stereoacuity is shown here for five spatial frequencies: 0.33 (□), 0.67 (■), 1.31 (○), 2.62 (●) and 5.24 (△) c/deg. The Gabor stimuli had a relatively broad bandwidth (1.13 octaves). As in the previous figure, error bars indicate ±1 SEM and the solid comparison line has a slope of −0.5.

FIGURE 4. (A, B) Performance error is plotted here as a functio:. of the separation between the central and peripheral Gabor patches. Data are shown from one subject, for broad (A) and narrow (B) bandwidth stimuli at two viewing distances. The broadband (1.13 octave) targets had centre frequencies of 0.66 (○) and 5.24 (□) with sizes (σ) of 45.8 and 5.7 min arc respectively. The narrow band (0.18 octave) targets had centre frequencies of 5.24 (□) and 10.4 (■) c/deg with σ = 34.4 and 17.2 min arc respectively. Separation is in terms of the size (σ) of the Gaussian envelope. Error bars indicate ±1 SEM.

fit to the data (but see also Cormack, Stevenson & Schor, 1991).

The only deviation from the preceding observation was seen in LMW's data at high spatial frequencies and low suprathreshold contrasts. Similar, but vertically displaced, functions are found for stimuli of different peak spatial frequency. These results suggest that a fixed suprathreshold contrast should be used for comparisons between stimuli of different peak spatial frequency. Therefore, in subsequent experiments we used a fixed suprathreshold contrast of 8 (LMW) or 12 (JH) dB.

Figure 4 shows the relationship between stereoacuity and the distance between the target and reference elements for one subject only. The results for broadband stimulus elements (1.13 octave bandwidth; SF = 0.66 and 5.24 c/deg) are displayed in Fig. 4(A) while the results for narrowband stimulus elements (0.18 octaves bandwidth; SF = 5.24 and 10.4 c/deg) are displayed in Fig. 4(B).

Separation is plotted in multiples of the size (σ) of the target Gaussian. For the broadband stimuli, stereoacuity does *not* depend on element separation for either of
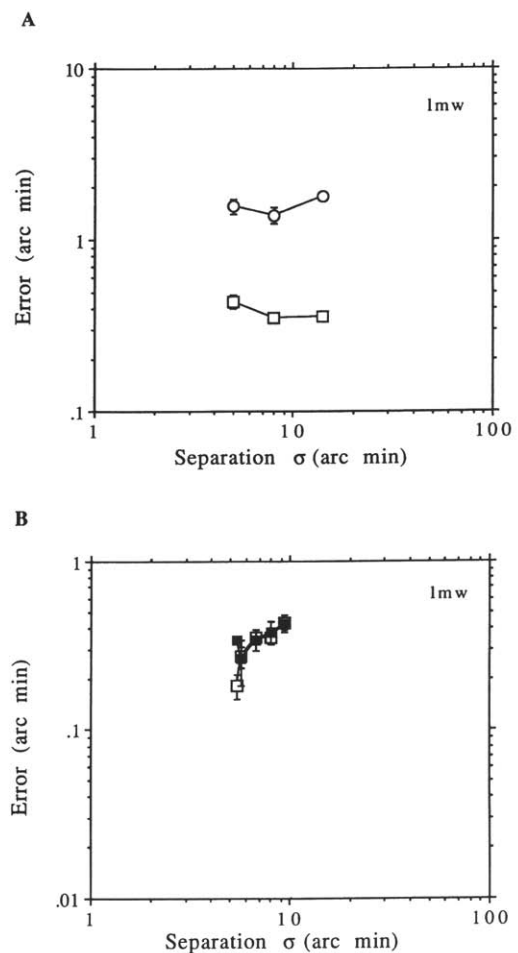
the spatial scales investigated. For the narrowband stimuli, there is a stronger dependence on separation which begins to asymptote at separations of 8 times the σ of the target Gaussian. However, because we do not use stimulus configurations which extent beyond this range, this is only an *effective* asymptote. In subsequent experiments stimulus elements were separated by a constant multiple of the σ of their Gaussian envelopes because stereoacuity for narrowband stimuli depends on this relative metric rather than on the absolute distance between elements (Fig. 4). Note that when the size of our stimulus elements is *scaled* the stimulus separation is also scaled accordingly. As mentioned previously we chose a distance equivalent to 8 times the gaussian σ as this corresponded to asymptotic performance. Thus we are confident that this aspect of the stimulus geometry would not be likely to have a significant effect on our results. The clear dependence of stereoacuity on the carrier spatial frequency for broadband stimuli [the vertical separation of
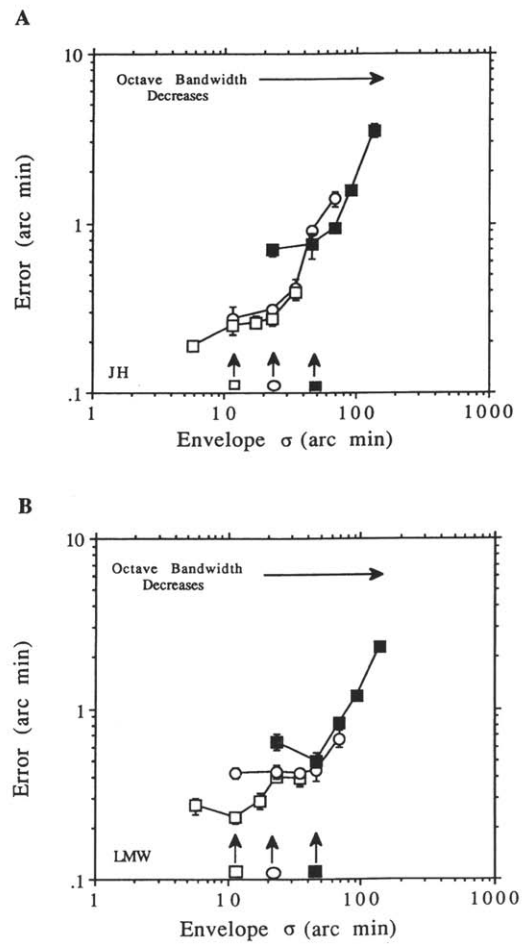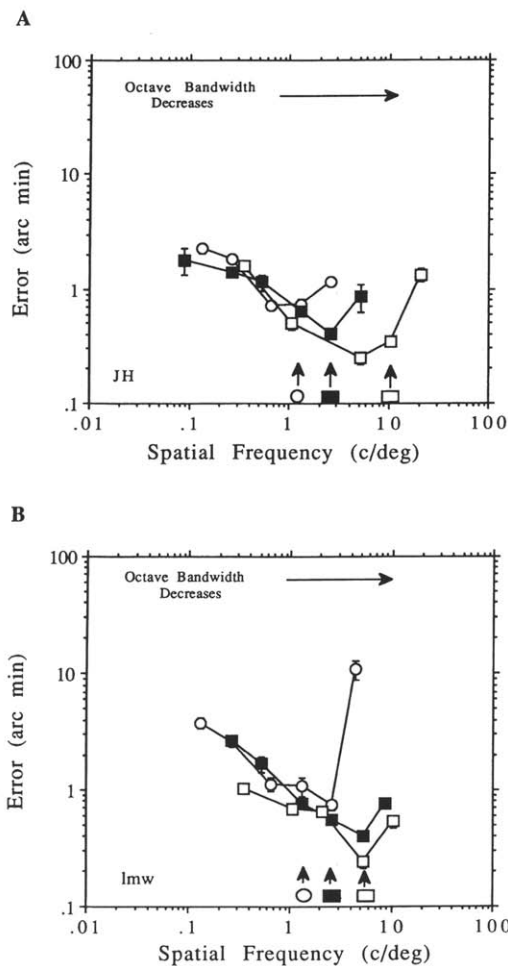
A

B

FIGURE 5. (A, B) Stereoacuity is plotted here as a function of the carrier frequency of the Gabor patches, for two subjects. Three envelope sizes were tested with $\sigma = 45.8$ (○), 22.9 (■) and 5.73 (□) min arc. Arrows along the x-axis indicate an octave bandwidth of 0.5 for each stimulus set and error bars indicate ±1 SEM.

A

B

FIGURE 6. (A, B) The effect of varying the envelope of the Gabor stimuli while the carrier frequency is fixed, is illustrated here. Results are shown for two subjects and three spatial frequencies: 1.31 (■), 2.62 (○), and 5.24 (□) c/deg. Arrows along the x axis indicate an octave bandwidth of 0.5 for each stimulus set and error bars indicate ±1 SEM.

the data evident in Fig. 4(A)] which is not observed for narrowband stimuli at any element separation, will be referred to later.

If stereoacuity was entirely determined by monocular localization signals, then there are some predictions as to how stereoacuity should depend on both spatial frequency of the carrier and the envelope size for these stimulus elements. For foveal vision, monocular spatial localization has been shown to be independent for the carrier frequency and linearly dependent on the envelope size for this task (Hess & Holliday, 1992). In the next two experiments we investigated the separate effects of these two parameters (carrier frequency and envelope size) on stereoacuity. The results displayed in Fig. 5(A, B) show, for two subjects, how stereoacuity varies with the carrier frequency of Gabor elements for Gabors of different sizes ($\sigma = 45.8$, 22.9 and 5.73 min arc).

For any one curve in Fig. 5 the size of the Gaussian envelope is fixed. There is a clear dependence of stereoacuity on the carrier frequency over most of the spatial frequency range for each of the three stimulus sizes. This breaks down at octave bandwidths

<0.5 (Fig. 5, arrows indicate 0.5 octave bandwidth). A vertical transect through these curves represent stereoacuity for a stimulus of one carrier spatial frequency but for different Gaussian envelope sizes and hence different numbers of cycles per envelope. Thus, the extent to which the curves overlap indicates that the relevant stimulus variable is *carrier spatial frequency* not overall Gaussian extent or even the number of cycles per envelope. The results of Fig. 4(A) also suggest that this dependence of stereoacuity on carrier spatial frequency occurs over a wide range of element separations. Therefore stereoacuity, unlike its counterpart for monocular spatial localization (Toet *et al.*, 1987; Toet & Koenderink, 1988; Hess & Holliday, 1992), exhibits a substantial dependence on the spatial frequency of the carrier over at least a decade range (5–0.5 octaves) which is independent of the envelope size. The slope of this relationship is slightly shallower than unity.

The complementary comparison, namely of the dependence of stereoacuity on the size of the Gaussian envelope for stimuli of different carrier spatial frequency is shown for two subjects (A and B) in Fig. 6. For
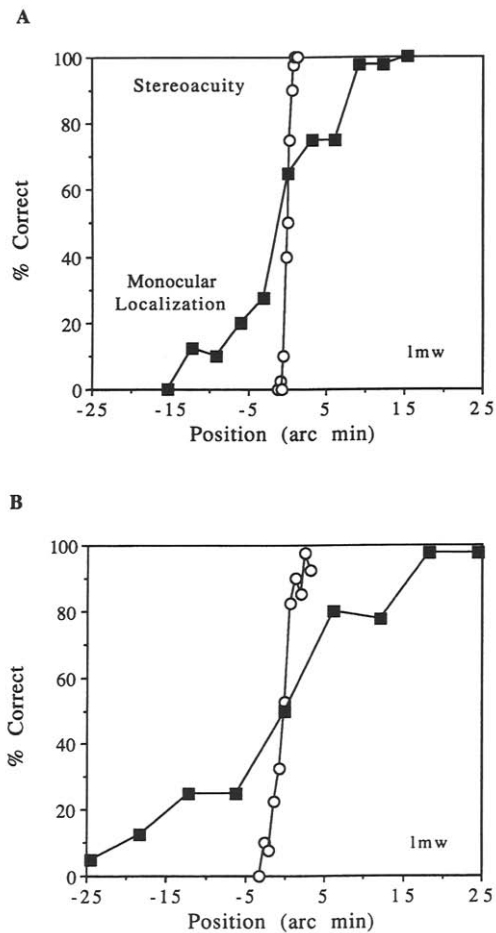
A

B

FIGURE 7. (A, B) Psychometric functions for monocular localization (■) and binocular stereoacuity (○) illustrate the dramatic difference between performance on the two tasks. Narrow band (0.18 octave) Gabor stimuli with carrier frequencies of either (A) 5.24 (σ = 34.4) or (B) 2.62 (σ = 68.7) c/deg were used in both conditions. Each curve represents the average of two psychometric functions for one subject (40 observations per point). At the highest frequency the estimate of error for stereoacuity was 0.34 (SE = 0.02) min arc, while the corresponding estimate for the monocular localization task was 6.66 (SE = 0.3) min arc. At the lower frequency, the error for stereopsis was 1.48 (SE = 0.14) min arc compared with error of 13.05 (SE = 0.37) min arc for monocular localization.

any one curve, the spatial frequency of the carrier is fixed (SF = 1.31, 2.62 and 5.24 c/deg) and the size of the Gaussian envelope is varied.

A vertical transect through these curves represents stereoacuity for a stimulus with one size of Gaussian envelope but different carrier spatial frequencies and hence different numbers of cycles per envelope. For bandwidths less than 0.5 octaves (Fig. 6, arrows indicate 0.5 octave bandwidth) a strong dependence is observed between stereoacuity and envelope size which is independent of both spatial frequency and octave bandwidth. The slope of this relationship is slightly steeper than unity on these log–log coordinates. The results of Fig. 4(B) also suggest that the lack of a dependence of stereoacuity on carrier spatial frequency is found over a wide range of element separations. For stimuli of broader spatial frequency bandwidth (> 0.5 octaves) stereoacuity no longer

depends on the Gaussian size but on the carrier spatial frequency (asymptotic regions of the curves in Fig. 6 at small envelope sizes). Thus for Gabor stimuli, the stereoscopic system can use the disparity information provided by either the carrier spatial frequency or the envelope size depending on the octave bandwidth of the stimulus.

Comparison with monocular localization

The present results highlight the importance of understanding the nature of early spatial frequency filtering operations in vision. The fact that for narrowband stimuli both monocular spatial localization and stereoscopic processing show a primary dependence on the size of the Gaussian envelope of these stimuli suggests that they both involve non-linear filtering. Furthermore, even when one uses spatially narrowband stimuli so that both monocular and stereoscopic localization rely on similar non-linear filtering operations, performance for the two tasks is very different. An example of this is shown in Fig. 7 where monocular and binocular localization performance has been compared for the same task (viewed binocularly or monocularly) in terms of the stimulus offset given to each eye. Two different spatial frequency narrowband (0.18 octaves) stimuli (SF = 2.62 and 5.24 c/deg; σ = 68.7 and 34.4 min arc respectively) were used for this comparison. In each case stereoacuity, given by the slope of the functions, is considerably better than monocular alignment (a factor of 9 for the lower and 19 for the higher frequency) even though both processes have similar initial, non-linear filtering operations for these narrowband stimuli. This superior stereoscopic localization performance can not be explained on the basis of summation of the two monocular inputs, and suggests that there may be differences in the more central localization stages for the two processes.

DISCUSSION

The early stages of visual processing involve a variety of spatial filtering operations and it is important to take this into account when comparing performance between different tasks. In order to understand the relationship between monocular and stereoscopic localization, we make a distinction between the initial filtering operations on the one hand and the more central computations for localization on the other.

The more central stage of stereoscopic localization has access to two different types of monocular information. It receives information not only from linear filters from which the spatial frequency dependence of steropsis is derived but also from the rectified output from linear filters from which the envelope size dependence is derived. Monocular spatial localization for these stimuli uses only the rectified output of linear filters to exact and localize the local contrast envelope (Toet, 1987; Toet et al., 1987; Toet & Koenderink, 1988; Kooi et al., 1990; Burbeck, 1988; Hess & Holliday, 1992). There are two possible explanations for the spatial frequency

dependence of stereopsis; it could be based on either the local spatial phase of the carrier frequency (Freeman & Ohzawa, 1990), or on the more global disparity of the Gabor stimulus. A recent study (Liu, Tyler, Schor & Ramachandran, 1992) has demonstrated that stereothresholds are higher when disparity is introduced by shifting the phase of the carrier relative to the Gaussian envelope than when both are shifted in concert. Since our stimuli are similar to theirs, and our measure of performance is also stereoacuity, it is tempting to conclude that this frequency dependence reflects operations performed on the disparity of the overall Gabor stimulus, rather than from the local spatial phase of its carrier.

The picture which emerges for stereopsis is not unlike that for motion (Sperling & Chubb, 1989; Boulton & Baker, 1993) and texture (Sperling & Chubb, 1989) where there is evidence for so-called "Fourier" and "non-Fourier" mechanisms underlying performance. For stereopsis, these mechanisms appear to have similar contrast, but different reference elements separation, dependencies. Further support for the existence of early non-linear filtering operations in stereopsis has been provided by a number of studies (Ramachandran, Madhusudhan Rao & Vidyasagar, 1973; Liu et al., 1992; Sato & Nishida, 1993; Wilson & Blake, personal communication).

Since we have shown that stereopsis has access to information derived from at least two types of early filtering, the exact interpretation of the differences that previous studies (Berry, 1948; Foley, 1976; Westheimer & McKee, 1979; Schor & Badcock, 1985; McKee et al., 1990) have revealed between monocular and stereoscopic localization should be re-evaluated. These could be attributed to either differences in early filtering or to differences at a more central stage. We demonstrate that for stimuli which equate the initial filtering operations for each process, stereoscopic localization is more precise (a factor of between 9 and 19 times). Therefore we conclude that there are important differences in the nature of the more central localization processes subserving monocular and stereoscopic localization.

Envelope size or spatial frequency content?

Can we recast the envelope-dependence reported above into a spatial frequency framework by assuming that stereoacuity varies not with the envelope size but with its high or low spatial frequency content?

High spatial frequency content. The high spatial frequency content of the stimuli whose results are shown in Fig. 6 are in the region where stereoacuity does not vary with spatial frequency (Schor & Wood, 1983). Therefore, if performance is solely limited by the high spatial frequency content of the envelope we would not expect stereoacuity to show any size dependence for our stimuli. Furthermore, even if our stimuli *were* in a range where stereoacuity depends on spatial frequency, our results show that stimuli of different peak spatial frequency, but the same envelope size result in comparable performance. This would not occur if stereoacuity simply depends on the highest spatial frequency supported by the envelope.

Low spatial frequency content. Our results demonstrate that stereoacuity *improves* as the Gaussian envelope narrows. An explanation for this based upon the changing (increasing) low frequency content of the envelope as its size decreases is not compatible with the spatial frequency dependence reported by Schor and Wood (1983). These authors showed that stereoacuity *declines* with decreasing spatial frequency for band-limited stimuli. Furthermore, any explanation of the improvement in stereoacuity with decreasing envelope size which is based on the increasing low spatial frequenty content is not supported by the results of Heckmann and Scor (1989) who showed that the addition of lower spatial frequencies does not improve stereoacuity.

The significance of stimulus bandwidth

We report here that the use of linear vs non-linear operations in stereopsis is contingent on the spatial frequency bandwidth (in octaves) of the stimulus. Figures 5 and 6 show that for spatially broadband Gabors, stereoacuity is determined by the carrier spatial frequency; at narrower bandwidths, performance on the same task is independent of the carrier frequency, but depends on the Gaussian envelope. The approximate bandwidth where this crossover occurs is 0.5 octaves, which corresponds to at least four cycles of the carrier function visible within the Gaussian envelope.

The question remains as to why the visual system might operate in this way. One possibility is that because of the spatial characteristics of the underlying detectors when there are fewer than four cycles of the carrier grating visible, maximum stereoacuity can be attained using the spatial frequency information present in the carrier. However, as the number of cycles increases, so too does the probability of making a false match. Given this correspondence problem, the spatial frequency of the carrier ceases to be a reliable source of information for stereopsis and the less precise estimate supplied by the envelope is used.

Relationship to previous studies

Schor and Wood (1983) were the first to explore the relationship between centre spatial frequency and stereoacuity for spatially bandpass stimuli. They showed that the relationship between centre spatial frequency, and stereoacuity between 2.0 and 0.075 c/deg is approximately linear. Schor and Wood (1983) used stimuli whose bandwidth at half height was 1.75 octaves. Since, for their stimuli, stimulus extent co-varied with the centre frequency it is not immediately obvious which of these two factors produced the relationship they reported. On the basis of the data presented here it would seem that for the bandwidth they used, stereoacuity depends on the spatial frequency content, as they concluded. However, for narrowband stimuli our results suggest that a similar functional dependence is observed which is due to the overall size of the stimuli rather than their spatial frequency content.

Relationship to neurophysiology

There is now ample evidence for the existence of neurons in the early retino–cortical pathway of the mammalian visual system with non-linear as well as linear filtering properties. For example, both y-cells and cortical complex cells exhibit a non-linearity which would enable them to extract the local contrast envelope from the output of their subunits. While it is possible that the linear and non-linear modes of stereopsis outlined here may be subserved by separate neuronal populations, for example simple and complex cells, this is not the only possibility. Recently a distinct population of cortical cells has been discovered (termed envelope responsive cells) which can operate in linear and non-linear modes (Zhou & Baker, 1993). These cortical cells perform a "double-duty" by processing separable signals relating to the luminance and envelope of visual stimuli. Thus the dichotomy reported here does not necessitate an explanation based on different cellular populations, one which extracts the frequency content, and another which extracts the overall size of spatially bandpass stimuli. Rather, this information may be encoded in a distributed fashion across the population of a single cortical cell type, namely the envelope responsive cells (Zhou & Baker, 1993). At present it is not known if these envelope responsive cells are also disparity selective.

REFERENCES

Berry, R. (1948). Quantitative relations among vernier, real depth and stereoscopic depth acuities. *Journal of Experimental Psychology, 28,* 708–721.

Boulton, J. & Baker, C. L. (1993). Different parameters control motion perception above and below a critical density. *Vision Research, 33,* 1803–1811.

Burbeck, C. A. (1988). Large scale relative localization across spatial frequency channels. *Vision Research, 27,* 417–427.

Cormack, L. K., Stevenson, S. B. & Schor, C. M. (1991). Interocular correlation, luminance contrast and cyclopean processing. *Vision Research, 12,* 2195–2207.

Foley, J. M. (1976). Successive stereo and vernier position discrimination as a function of dark interval duration. *Vision Research, 16,* 1269–1273.

Freeman, R. D. & Ohzawa, I. (1990). On the neurophysiological organization of binocular vision. *Vision Research, 30,* 1661–1676.

Halpern, D. L. & Blake, R. R. (1988). How contrast affects stereoacuity. *Perception, 17,* 483–495.

Heckmann, T. & Schor, C. M. (1989). Is edge information for stereoacuity spatially channeled? *Vision Research, 29,* 593–607.

Hess, R. F. & Holliday I. (1992). The coding of spatial position by the human visual system: Effect of spatial scale and contrast. *Vision Research, 32,* 1085–1097.

Kooi, F. L., De Valois, R. L. & Switkes, E. (1991). Spatial localization across chanels. *Vision Research, 31,* 1627–1632.

Legge, G. E. & Gu, Y. (1989). Stereopsis and contrast. *Vision Research, 29,* 989–1004.

Liu, L., Tyler, C. W., Schor, C. M. & Ramachandran, V. S. (1992). Positional disparity is more efficient in encoding depth than phase disparity. *Investigative Ophthalmology and Visual Science (Suppl.), 33,* 1373.

Mayhew, J. E. & Frisby, J. P. (1978). Stereopsis masking in humans is not orientationally tuned. *Perception, 7,* 431–436.

McKee, S. P. & Westheimer, G. (1978). Improvement in vernier acuity with practice. *Perception & Psychophysics, 24,* 258–262.

McKee, S. P., Levi, D. M. & Bowne, S. F. (1990). The imprecision of stereopsis. *Vision Research, 30,* 1763–1779.

McKee, S. P., Welch, L., Taylor, D. G. & Bowne, S. F. (1990). Finding the common bond: Stereoacuity and other hyperacuities. *Vision Research, 30,* 879–891.

Ramachandran, V. S., Madhusudhan Rao, V. & Vidyasagar, T. R. (1973). The role of contours in stereopsis. *Nature (London), 242,* 412–414.

Sato, T. & Nishida, S. (1993). Second order depth perception with texture-defined random check stereograms. *Investigative Ophthalmology and Visual Science (Suppl.), 34,* 1438.

Schor, C. M. & Badcock, D. R. (1985). A comparison of stereo and vernier acuity within spatial channels as a function of distance from fixation. *Vision Research, 25,* 1113–1119.

Schor, C. M. & Wood, I. (1983). Disparity range for local stereopsis as a function of luminance spatial frequency. *Vision Research, 23,* 1649–1654.

Sperling, G. & Chubb, C. (1989). Apparent motion derived from spatial texture. *Investigative Ophthalmology and Visual Science (Suppl.), 30,* 161.

Stigmar, G. (1970). Observations on vernier and stereoacuity with special reference to their relationship. *Acta Ophthalmologica, 48,* 779–799.

Stigmar, G. (1971). Blurred visual stimuli: The effect of blurred visual stimuli on vernier and stereo stimuli. *Acta Ophthalmologica, 49,* 364–379.

Stratton, G. M. (1900). A new determination of the minimum visible and its bearing on localization an binocular depth. *Psychological Review, 7,* 429–435.

Toet, A. (1987). Visual perception of spatial order. PhD thesis, University of Utrecht, The Netherlands.

Toet, A. & Koenderink, J. J. (1988). Differential spatial displacement discrimination of Gabor patches. *Vision Research, 28,* 133–143.

Toet, A., von Eekhout, M. P., Simons, H. L. J. J. & Koenderink, J. J. (1987). Scale invariant features of differential spatial displacement discrimination. *Vision Research, 27,* 441–452.

Tyler, C. & Barghout, L. (1992). Multiple channels in stereoscopic masking: A computational analysis. *Investigative Ophthalmology and Visual Science (Suppl.), 33,* 1334.

Westheimer, G. & McKee, S. P. (1979). What prior uniocular processing is necessary for stereopsis. *Investigative Ophthalmology and Visual Science, 18,* 614–621.

Wheatstone, C. (1838). Contributions to the physiology of vision. 1 On some remarkable and hitherto unobserved, phenomena of binocular vision. *Transactions of the Philosophical Royal Society of London, 128,* 371–394.

Wilcox, L. M. & Hess, R. F. (1993). Linear and non-linear contributions to stereopsis. *Investigative Ophthalmology and Visual Science (Suppl.), 34,* 2382.

Yang, Y. & Blake, R. (1991). Spatial frequency tuning of human stereopsis. *Vision Research, 31,* 1177–1189.

Zhou, Y.-X. & Baker, C. L. Jr (1993). A processing stream in mammalian visual cortex for non-Fourier responses. *Science, 261,* 98–101.