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The Effect of Spatial Frequency and Field Size on the Spread of Exclusive Visibility in Binocular Rivalry

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We measured binocular rivalry between dichoptic, orthogonal, sinusoidal gratings both having spatial frequencies of 0.5, 1, 2, 4, 8 or 16 c deg^{-1} in fields ranging from 0.5 to 8 deg of visual angle in diameter. Total time that one or the other grating was exclusively visible had an inverted U-shaped relationship with spatial frequency, with the peak shifting to coarser spatial frequencies as the field size increased. We computed for each spatial frequency the maximum field size over which a criterion duration of exclusive visibility would spread. When expressed as areas, these sizes were inversely proportional to spatial frequency. This dependence of rivalry on spatial frequency is similar to those for stereopsis and fusion, consistent with the notion that all three binocular phenomena have a common mechanism. Copyright © 1996 Elsevier Science Ltd

Binocular rivalry Spatial frequency Field size Exclusive visibility

INTRODUCTION

The separation of the two eyes by a few centimetres means the left eye's retinal image of an object is slightly different from the right eye's retinal image. Depending on the nature and magnitude of the differences, three major binocular phenomena can be experienced: fusion; stereopsis; and rivalry. When the differences between the retinal images of an object are very slight, binocular fusion occurs, that is, perception is of a single object. When the differences yield moderate values of horizontal disparity, stereopsis occurs, that is, the object is seen in depth. When the images are very different, binocular rivalry occurs (Breese, 1899), that is, perception oscillates between one eye's image and the other's.

Schor *et al.* (1984a,b), using spatial-frequency band-limited bars (difference-of-Gaussian bars; we will refer to these as DOG bars) have shown that disparity limits of both fusion and stereopsis are inversely proportional to spatial frequency: at high spatial frequencies, the disparities yielding fusion and stereopsis are smaller than at low spatial frequencies. This suggests that fusion and stereopsis have a common mechanism. We wanted to determine whether binocular rivalry depends similarly on spatial frequency, which might suggest that all three binocular phenomena have a common mechanism.

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Liu and Schor (1994) offer suggestive evidence for an inversely proportional relationship between binocular rivalry and spatial frequency. They presented a horizontal DOG bar to one eye, then flashed for 1 sec a pair of vertical DOG bars to the other eye. They varied the separation of of the vertical DOG bars to find the largest at which all of the horizontal DOG bar was invisible between the vertical DOG bars. They found that as the spatial frequency of the stimuli increased, this largest separation decreased proportionally. Although it is likely that the 1 sec suppression of visibility of the horizontal DOG bar was from binocular rivalry, at least one other mechanism is possible. That is, Liu and Schor's flash suppression may represent some form of dichoptic masking (*cf* Abadi, 1976), so cannot be taken as definitive evidence for a inversely proportional relationship between binocular rivalry and spatial frequency.

We are aware of only one study in which traditionally defined binocular rivalry, involving numerous alternations between two stimuli over an extended observation period, has been measured as a function of spatial frequency of sinusoidal gratings. Hollins (1980) measured the amount of time one or the other of two rival gratings was exclusively visible over 100 sec trials. The rival gratings were vertical to one eye and horizontal to the other, viewed in a 2 deg field. Instead of an inversely proportional relationship between exclusive visibility of binocular rivalry and spatial frequency, Hollins (1980) found a curvilinear relationship peaking at 3 c deg^{-1}.

We suspected that Hollins's (1980) failure to find an

TABLE 1. Summary of *F* values for the interaction between field size and spatial frequency (d.f.=20, 90)

Observer	Dependent variable		
	Exclusive visibility	Rate	Period†
RB	16.65****	22.89****	0.34
AS	13.08****	17.75****	0.86
ROS	7.54****	6.95****	1.10
SH‡	8.36****	8.06****	0.21

****$P < 0.0001$.
†d.f.s for periods were less than (20, 90); see text.
‡d.f. for SH were (20, ≥25).

inversely proportional relationship between binocular rivalry and spatial frequency was because he kept the size of the field containing his stimuli constant. That is, more grating bars were visible with high spatial frequencies than with low spatial frequencies. The reduced number of bars may account for the decrease in exclusive visibility for spatial frequencies below 3 c deg^{-1} (*cf* Levelt, 1968). We decided to search for an inversely proportional relationship between rivalry and spatial frequency over a range of field sizes.

METHODS

Observers

Three males and one female volunteered for the experiment. RB and ROS were very experienced rivalry observers. AS and SH were inexperienced in observing rivalry. All observers had normal or corrected-to-normal vision and good stereopsis.

Apparatus

A compiled Pascal program running on a Macintosh IIcx computer controlled the experiment. Stimuli were displayed on two Apple, high resolution, 12", monochrome monitors (67 Hz Model MO400). A Minolta Chroma Meter (model CS-100) was used to calibrate and linearize light output of the monitors. A mirror stereo-

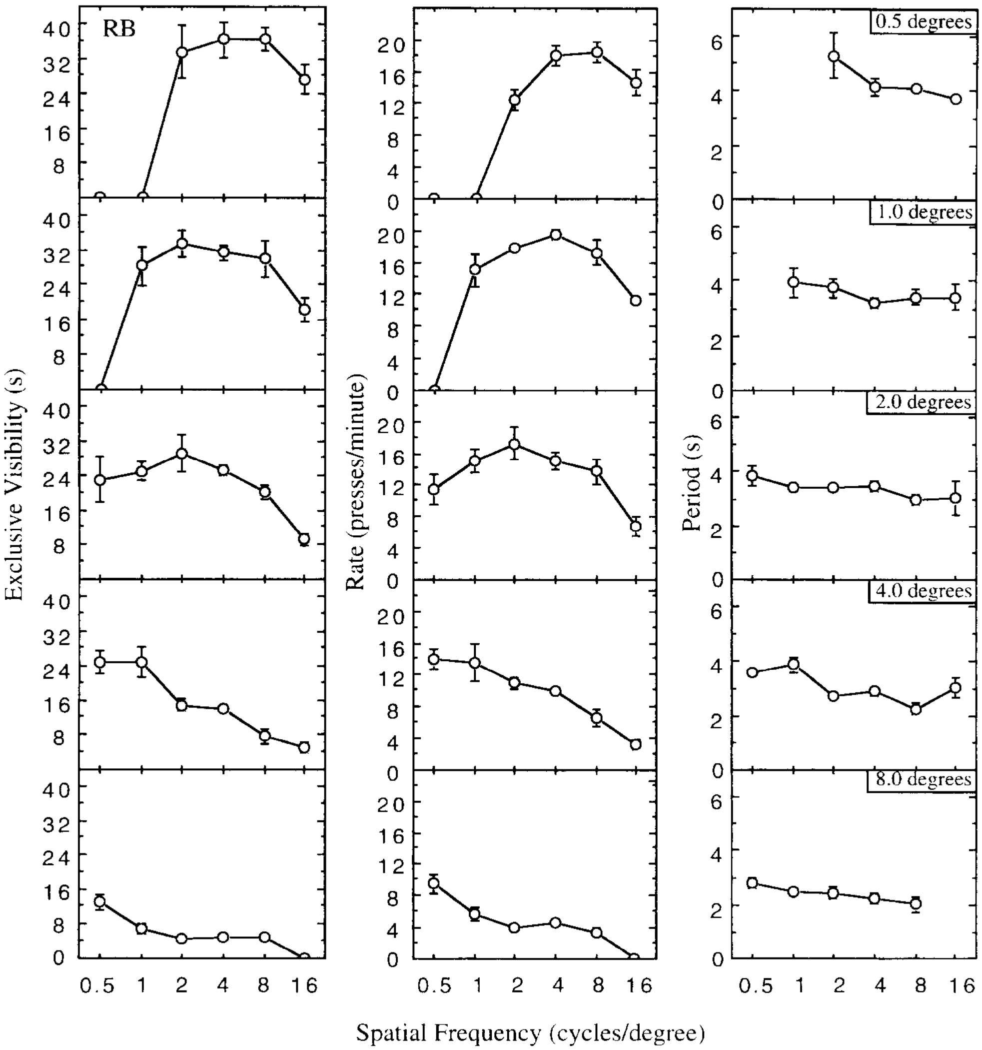

FIGURE 1. RB's mean exclusive visibility (column 1), rate (column 2) and period (column 3) as a function of spatial frequency. Each graph represents a different field size. Except for the period data (see text), each point represents the mean of four trials. The vertical bars show ±1 SEM.

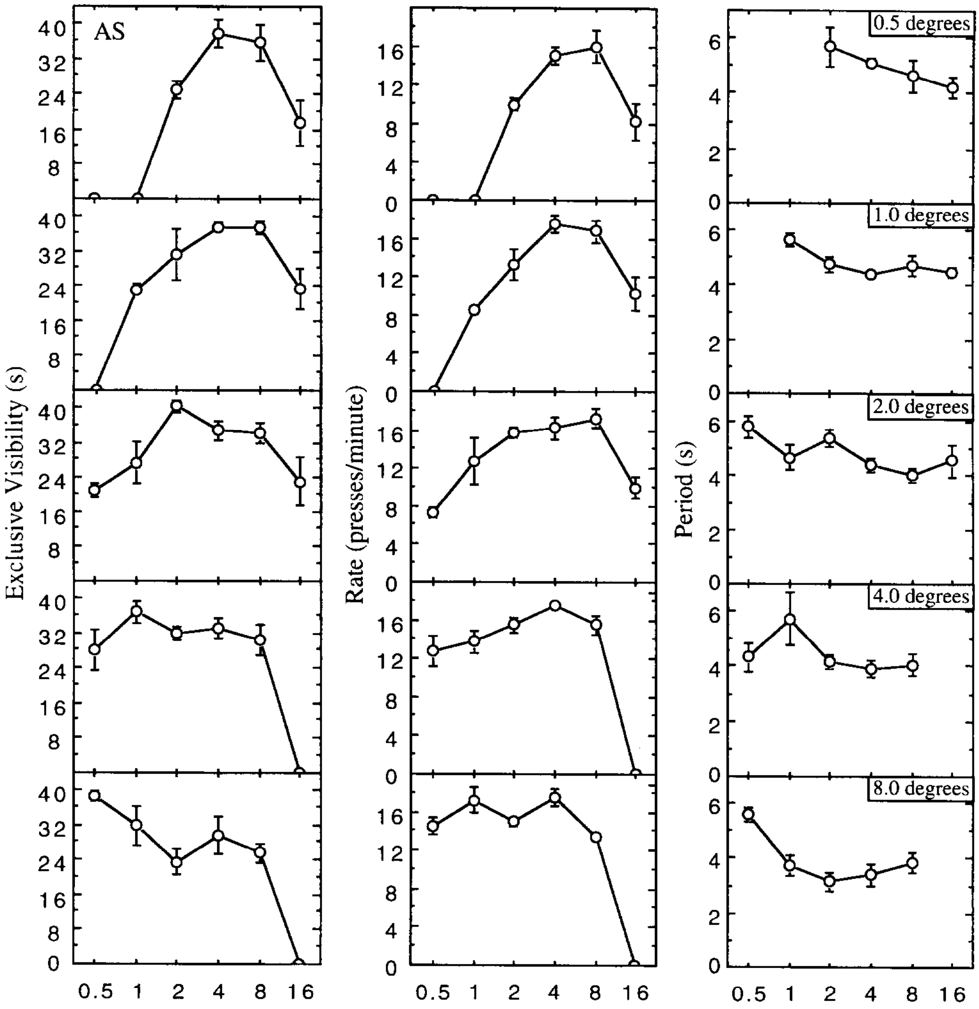

FIGURE 2. AS's mean exclusive visibility (column 1), rate (column 2) and period (column 3) as a function of spatial frequency. Each graph represents a different field size. Except for the period data (see text), each point represents the mean of four trials. The vertical bars show ±1SEM.

scope enabled each eye to view a separate monitor. The total viewing distance was 1.12 m.

Stimuli

Each stimulus was a sinusoidal grating displayed within a circular field on the screen of a monitor. One grating was horizontal; the other was vertical; both were the same size on each trial. Size of the gratings varied across the trials, subtending a diameter of 0.5, 1.0, 2.0, 4.0 or 8.0 deg visual angle. The screens measured 8.0 deg vertically and 10.7 deg horizontally. Spatial frequency varied across trials, being 0.5, 1.0, 2.0, 4.0, 8.0 or 16.0 c deg^{-1}. The mean luminance of the gratings was 48.5 cd m^{-2} and the contrast was 0.8. The background luminance of the screen was 6.0 cd m^{-2}. At the extreme left and right sides of the screen, single white vertical bars 0.50 deg wide and 8.0 deg high provided a vergence lock. The luminance of these bars was 100.0 cd m^{-2}.

Procedure

Each trial began with a tone. To show the stimuli, observers pressed both response keys simultaneously. Observers were asked to keep fixation approximately in the centre of the field, but to move their eyes if the gratings began to fade. Observers pressed the left key when vertical bars were exclusively visible over the whole field, the right key when horizontal bars were exclusively visible over the whole field, and neither key when both were partially visible. Each trial lasted 1 min and was followed by an inter-trial interval of at least 45 sec. This procedure yields three dependent variables: exclusive visibility (i.e. the cumulative time the buttons were depressed per minute); rivalry rate (i.e. the total number of button presses per minute); and rivalry period (i.e. the average time each button was depressed).

The five field sizes and six spatial frequencies were factorially crossed with orientation/eye arrangement (i.e. vertical presented to the left eye and horizontal presented

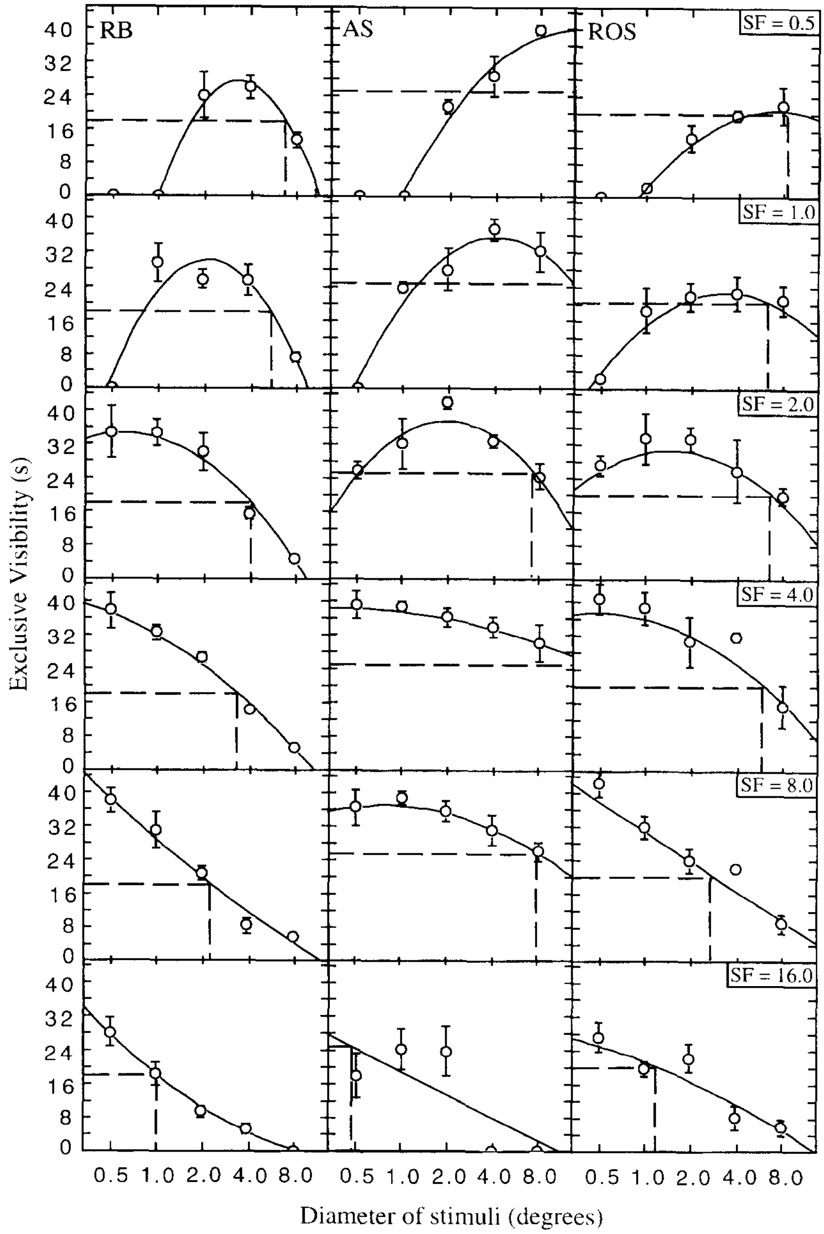

FIGURE 3. Functions relating exclusive visibility to field size at different spatial frequencies for RB, AS and ROS. The functions are all quadratic, except for AS's 16 c deg^{-1} graph, where a linear function has been plotted. The horizontal dashed line on each graph shows that observer's mean exclusive visibility over all trials. The vertical dashed line marks where the horizontal dashed line meets the function, giving the abscissa: the diameter at which stimuli of a particular spatial frequency yield the mean amount of rivalry. At low spatial frequencies, and for most of AS's functions, this abscissa is above the limits of the graph, requiring extrapolation.

to the right eye, VH vs HV) to yield a block of 60 trials. These were presented in random order for each observer. Observers ROS, RB and AS then responded to another block of 60 trials given in a new random order. Observers responded to trials in sessions no longer than 1 hr, separated by at least 24 hr. Prior to formal data collection, AS and SH participated in at least 30 practice trials.

RESULTS AND DISCUSSION

The three dependent variables were analysed separately for observers RB, AS and ROS using three-factor analyses of variance (ANOVAs) with block as the replicate. For SH, who ran only one block, we performed a two-factor ANOVA using orientation/eye arrangement as the replicate. All observers showed significant interactions between field size and spatial frequency for exclusive visibility and rate (see Table 1), and no other significant interactions.

The patterns of means contributing these significant interactions were similar in all four observers. Results from observers RB and AS are presented in Figs. 1 and 2, respectively. The figures show, from left to right, mean exclusive visibility, rate, and period as a function of

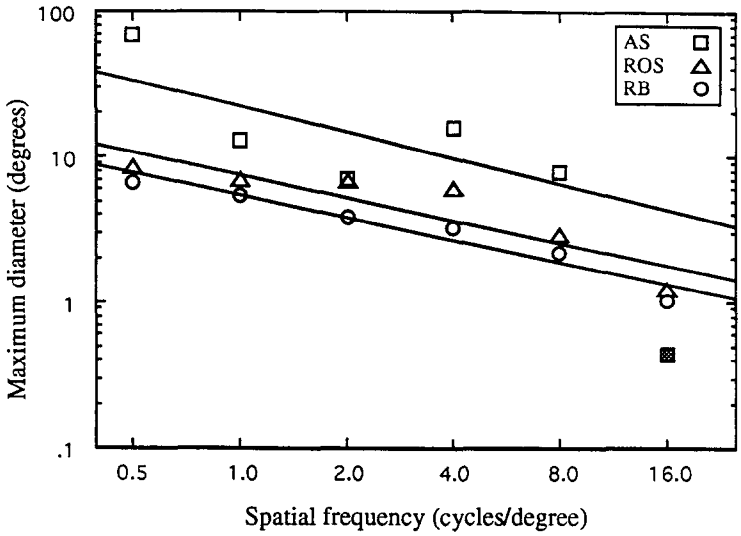

FIGURE 4. Plots of the relationship between stimulus field diameter yielding mean exclusive visibility and spatial frequency for observers RB, AS and ROS. The lines are lines of best fit with slopes as shown in Table 2. The gray point for AS was estimated by linear regression.

spatial frequency. From top to bottom, the figures show graphs for the five field sizes, from the smallest to the largest.

Exclusive visibility and rate show inverted U-shaped functions of spatial frequency with their peaks shifting to lower spatial frequencies as the field size increases. The graph of exclusive visibility for a field size of 2 deg dia (leftmost graph, third from the top in Figs 1 and 2) reproduces the conditions, and approximate result, of Hollins (1980). That is, he found peak rivalry at a spatial frequency of 3 c deg^{-1}; we found peak rivalry at 2 c deg^{-1} (we did not test 3 c deg^{-1} stimuli). Note, however, that the peaks of these functions depend on the field size: with a field size of 0.5 deg, the peak is at about 4 c deg^{-1}; with a field size of 4.0 deg, the peak is at about 1 c deg^{-1}.

The inverted U-shaped functions of rate and exclusive visibility with spatial frequency may be explained by two separate mechanisms. First, the left branch of the inverted U could reflect the influence of low numbers of cycles in displays. For example, consider a vertical 1.0 c deg^{-1} grating in a 0.5 deg field. Only half a cycle of this grating would be displayed. This stimulus would have a complex Fourier spectrum, with low power at 1.0 c deg^{-1} for vertical. When we consider the spectrum of its rival partner, a horizontal grating, we see that there is little reason to expect rivalry, because there is similar low power at 1.0 c deg^{-1} for horizontal. Moreover, most of the power in both rival gratings resides in spatial frequencies of the same orientation in the two eyes, arising from the identical edges of the grating surround. That is, fusable contours may inhibit weak rivalry arising from displays containing low numbers of cycles.

Second, the right branch of the inverted U may reflect some inability of exclusive visibility to spread over more than about 4–8 cycles of grating. As we will argue in the General Discussion, this could represent some fixed limit on spread of exclusive visibility as a function of spatial frequency, reflecting a limit on cooperative interactions between cortical hypercolumns.

We analysed periods from trials in which there were at least five episodes of exclusive visibility (any fewer than these produced unstable means; in fact, most of these trials had no episodes of exclusive visibility, for which a period cannot be computed). As can be seen in Table 1, and in Figs. 1 and 2, no observer showed a significant interaction, allowing us to look at main effects. There is essentially no influence of spatial frequency on periods. For RB, AS, ROS and SH, $F(5, \geq 38) = 0.82$, 2.25, 1.04 and 0.85, respectively, all $P > 0.05$. With the exception of SH, $F(4, 45) = 1.19$, $P < 0.4$, field size strongly influences periods. For RB, AS and ROS, as field size increases, periods consistently decrease, $F(4, \geq 85) = 11.08$, 3.25, 8.80, all $P < 0.05$, respectively. This is similar to the general decrease in periods with increasing field size reported by Breese (1909).

To determine whether spread of exclusive visibility in rivalry is inversely proportional to spatial frequency, we used a similar technique to that used by Blake *et al.* (1992) to quantify the spread of exclusive visibility in rivalry: we replotted the exclusive-visibility data against field size with spatial frequency as the parameter for RB, AS and ROS, omitting SH's data because she had only two observations per condition, compared with four for the other observers. We then fitted a quadratic function to each set of raw, spatial-frequency data. In deriving these functions, we excluded the 0.5 deg field for the 0.5 c deg^{-1} gratings; this condition yielded no rivalry for any observer. We calculated a criterion amount of rivalry for each observer: the mean exclusive visibility for each observer over all trials. Then we used the quadratic functions to determine the maximum field diameter that yielded this criterion amount of rivalry, using extrapolation if necessary. (One such function, that

TABLE 2. Summary of linear regression between spatial frequency and the maximum diameter yielding mean exclusive visibility

Observer	Slope	Intercept	r†
RB	−0.50	0.73	0.96**
AS	−0.59	1.36	0.72‡
ROS	−0.52	0.88	0.90*

*$P < 0.05$; **$P < 0.01$.

†The test of significance was by ANOVA on the slope of the regression line. d.f. for RB and ROS were (1, 4), for AS were (1, 3).

‡$P < 0.2$ when we omit the point at 16 c deg^{-1}. Recall that this was the only point we could not derive from a quadratic function. Although AS's regression is significant ($P < 0.05$) when we include the 16 c deg^{-1} point, it doubles his slope. Given the similarity of the displayed slope parameter to those of RB and ROS, we decided to exclude the 16 c deg^{-1} point, thereby retaining his slope of −0.59.

for 16 c deg^{-1}, for AS, failed to intersect this criterion. We used linear regression, therefore, to derive a datum for this condition.) The data, the functions, and how the criterion amount of rivalry was used to determine the field size, are illustrated in Fig. 3. For example, RB's mean exclusive visibility over all trials was 17.80 sec. For 2 c deg^{-1} stimuli (leftmost graph, third from the top of Fig. 3), this criterion yielded a maximum diameter of 3.97 deg.

In Fig. 4, we have plotted the diameters found in Fig. 3 as a function of spatial frequency for each observer.* We used linear regression to produce the lines on the figure. Table 2 gives a summary of these analyses.

Although the intercepts for the observers differ, possibly reflecting individual differences in criterion for reporting rivalry, all consistently show a slope of about −0.5. That is, the maximum diameter of a region over which exclusive visibility will spread is inversely proportional to the square root of the spatial frequency.

GENERAL DISCUSSION

Our data show that the spread of exclusive visibility in binocular rivalry is large for low-spatial-frequency stimuli, and small for high-spatial-frequency stimuli. In this, rivalry is similar to fusion and stereopsis in its dependence on spatial frequency, and is consistent with the idea that all three phenomena have a common mechanism. Moreover, our data map the relationship between rivalry and spatial frequency (0.5–16 c deg^{-1}) over field size (0.5–8 deg) to realistic limits.

*For RB and ROS, the two most experienced observers of rivalry, reducing the criterion duration of exclusive visibility did not affect the shape, or slope of the function relating diameter to spatial frequency; it only raised the intercept. For AS, however, reducing the criterion exclusive visibility preferentially raised the diameters for spatial frequencies of 4 and 8 c deg^{-1}. This can be seen in Fig. 3, where the general level of AS's exclusive visibility for these spatial frequencies is higher than for all his other spatial frequencies. We are not sure why AS's results differed in this respect from those of RB and ROS.

Could our spatial-frequency/field-size map be bigger?

To increase the largest field size to 16 deg would have presented most of the area of the field to peripheral vision with its attendant complications for rivalry (*cf* Blake *et al.*, 1992) and visibility. Indeed, for the 16 c deg^{-1} grating in the 8 deg field, all observers noted that they could resolve only an inner region of the grating of about 6 deg in diameter (in this case, the observers reported exclusive visibility only for the part of the grating they could see).

To reduce field size to 0.25 deg dia would guarantee no rivalry for low spatial frequencies. At spatial frequencies above about 4.0 c deg^{-1}, however, this and even smaller field sizes may yield appreciable rivalry (see Fig. 3). This size might be considered a realistic limit, however, because it is of the order of Panum's fusional area as traditionally defined (e.g. Ogle, 1950) with spatially complex stimuli. It may be that any disparity (including those arising from orthogonal orientations) smaller than Panum's fusional area would be fused. Yet when we made qualitative observations with a 16 c deg^{-1} grating in a 0.25 deg field, we observed rivalry. This rivalry emphasizes that Panum's fusional area is not a fixed-size region within which all disparities will be fused, but that extent of fusion and rivalry depend on the spatial-frequency content of the stimuli (Liu & Schor, 1994; Schor *et al.*, 1984a,b).

To expand the range of spatial frequencies we tested to include 0.25 and 32 c deg^{-1} would be to approach the contrast sensitivity limits of our observers. Recall that we used a contrast of 0.8. This contrast should be sufficiently above the contrast threshold for each spatial frequency to ensure contrast constancy over the range we used (*cf* Georgeson & Sullivan, 1975), ensuring that our results are not confounded by variations in visibility.

Relationships between binocular phenomena and spatial frequency

In Fig. 5 we have plotted against spatial frequency the spatial limits of binocular fusion and stereopsis (Schor *et al.*, 1984a,b), binocular suppression (Liu & Schor, 1994), and spread of exclusive visibility in binocular rivalry (our results). This figure illustrates the similarities and differences of the relations between the three binocular phenomena and spatial frequency.

For a fusional task that does not involve stereopsis (fusing over vertical disparities, filled circles), the maximum disparity is inversely proportional to spatial frequency over the full range studied. When fusing over horizontal disparities, however, Schor *et al.* (1984a) found a constant disparity limit for spatial frequencies above about 2.4 c deg^{-1}, suggesting either two components of the fusion mechanism, or the influence of stereopsis processing.

For static stereopsis, there is an inversely proportional relation between minimal disparities (upright triangles) and spatial frequency up to about 2.4 c deg^{-1}, after which the function flattens. Schor *et al.* (1984a,b) suggest there are two components of the stereopsis mechanism:

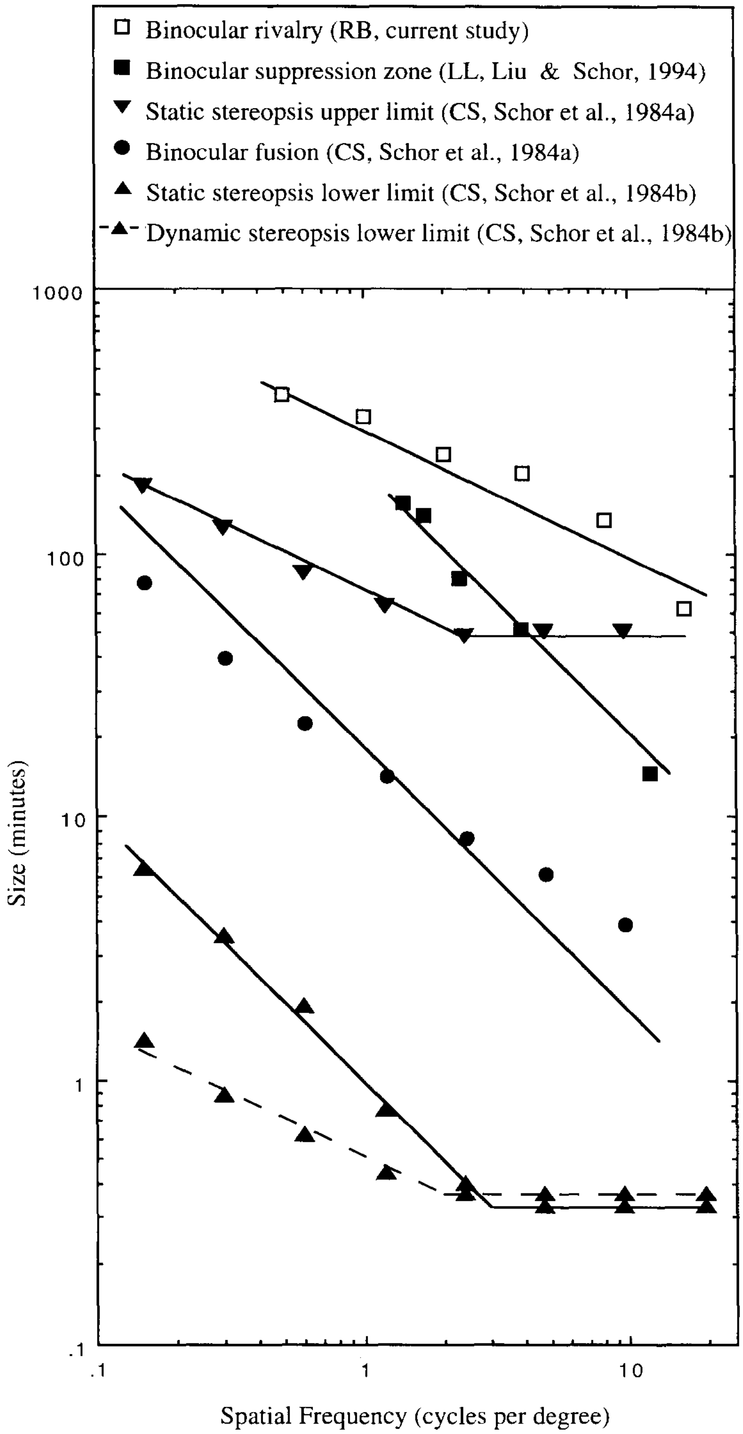

FIGURE 5. Summary of the relationships between spatial frequency and the spatial limits of fusion (circles), stereopsis (triangles) and rivalry (squares). The lines on the figure have slopes -1.0, -0.5 and 0.0. The filled symbols show (mainly CS's) data from published research, the open squares show RB's data from the current study. CS's data for the suppression zone showed a horizontal branch for spatial frequencies higher than about 2.4 c deg^{-1}, so we have instead plotted LL's more typical data showing a continual decrease with spatial frequency.

one that depends proportionally on spatial frequency at low and moderate spatial frequencies, and one that accepts constant-sized disparities for higher spatial frequencies. For maximal disparities with static stereopsis (inverted triangles) and minimum disparities with dynamic stimuli (upright triangles with dashed line), the form of the functions is similar, but the slopes for spatial frequencies <2.4 c deg^{-1} are equal to -0.5, showing a square-root, rather than a proportional, relation with spatial frequency. It is unclear why these various slopes differ for different aspects of stereopsis,* but what can be

*Wilcox and Hess (1995) point out that in these studies, spatial frequency covaries with size. They have evidence that the maximum disparity allowing stereopsis depends more on the size of a stimulus than on its spatial frequency.

emphasized is the similarity of the general form of all three limits.

For orthogonal stimuli that yield rivalry, the maximum separation of vertical DOG bars yielding complete suppression of an intervening horizontal DOG bar (filled squares), and the diameter of the area over which exclusive visibility will spread (open squares), decline monotonically with spatial frequency. Although the two suppression phenomena have different slopes (-1.0 and -0.5, respectively), we will argue below that the two involve similar processing.

What is the relationship between spread of exclusive visibility in rivalry and spatial frequency?

Earlier, we suggested that Liu and Schor's (1994) measurement of a binocular suppression zone (filled squares) might involve processing other than rivalry. This might seem likely from Fig. 5 because the slope of their spatial-frequency function (filled squares) on log–log scales is twice what we found (open squares). We agree with Liu and Schor, however, that their phenomenon did involve rivalry. They reported episodes of incomplete and changing suppression of the intervening horizontal DOG bar at larger-than-optimal separations. These are consistent with the qualitative properties of rivalry. Moreover, the difference in slope can be reconciled.

Liu and Schor's (1994) data are the maximal separations between two vertical DOG bars that will allow no part of a horizontal DOG bar viewed by the other eye to be seen between the two vertical DOG bars. The function has a slope of -1 with spatial frequency. Liu and Schor propose that each vertical DOG bar has a suppression zone surrounding it. To cover an intervening horizontal DOG bar, therefore, these two suppression zones must overlap. Liu and Schor's procedure estimates the horizontal dimensions of the suppression zones surrounding vertical DOG bars, but not their vertical dimensions.* The vertical dimension must be such as to cover the vertical extent of the horizontal DOG bar, but we do know whether it extends all the way along the vertical contours, or has an extent similar to its horizontal extent.

Research by Fukuda and Blake (1992), who measured the influence on rivalry in a central pair of gratings by rivalry occurring in a surrounding annulus, suggests the vertical and horizontal extents of suppression zones must be similar. In that case, Liu and Schor's criterion of rivalry depends only on the horizontal dimensions of the suppression zone, the vertical suppression zone being irrelevant because it fortuitously covers the vertical extent of the horizontal DOG bar. If the horizontal extent of these suppression zones is inversely proportional to the spatial frequency, then their criterion of rivalry will be similarly dependent.

*Liu and Schor rotated their entire display to estimate the vertical size of the suppression zones surrounding horizontal DOG bars. They found a similar dependence on spatial frequency, although, interestingly, its slope was steeper than -1.

In our study, however, for rivalry to be reported, one grating had to be exclusively visible over the complete *area* of the field. Blake *et al.* (1992) outlined a model in which rivalry dominance initially develops independently in many nonoverlapping suppression zones, but then, through cooperative interactions, adjacent zones all resolve into the same state of dominance, allowing exclusive visibility. That is, many zones processing an *area* of the visual field occupied by the rival stimuli must cooperate to yield exclusive visibility. If we were to replot our observers' data in terms of area (equal to the square of half the plotted diameters times π), the slopes would be doubled to about -1, agreeing with that found by Liu and Schor (1994).

Our current results suggest Blake and colleagues' (1992) model needs to be modified in at least one of two ways: either the visual area over which fixed-size zones will cooperate in the same dominance state is inversely proportional to the spatial frequency of the stimuli, or the diameter of each suppression zone is inversely proportional to spatial frequency. If stereopsis and fusion are accomplished within single zones, tentatively identified as the receptive fields of cortical hypercolumns, parsimony would suggest the latter. The idea that the receptive fields of cortical hypercolumns can change depending on the spatial properties of the input was broached by O'Shea *et al.* (1994).

Our results also provide evidence against Livingstone and Hubel's (Livingstone & Hubel, 1987) claim that binocular rivalry is confined to the magnocellular pathway of the visual system. In support of this, they demonstrated that high-spatial-frequency rival lines tended not to rival. We note, however, that their demonstration stereogram contains very large fields; under these conditions, we also found very little rivalry. Yet our results show that when the field size is reduced, rivalry is perceived for high-spatial-frequency rival lines.

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