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Determinants of fusion of dichoptically presented orthogonal gratings

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Abstract. Liu, Tyler, and Schor (1992 *Vision Research* **32** 1471 – 1479) reported the surprising finding that dichoptically presented orthogonal sine-wave gratings do not always produce binocular rivalry. Gratings of high spatial frequency, and especially of low contrast, fuse to produce a stable percept of a dichoptic plaid. Using a somewhat different perceptual task, we replicated those findings and extended them. The probability of a plaid percept is higher for square-wave gratings than for sine-wave gratings, and higher still for rectangular-wave gratings with high duty cycles (with very thin light or dark bars). Experiments were conducted to test whether this duty-cycle effect was due to changes in overall luminance, or in the size of the regions of luminance congruity (which may reduce the probability of rivalry), but no such effects could account for the results. The presence of locally conflicting contour information in the two eyes was shown to be an important determinant of rivalry onset, but, since removing such regions did not eliminate rivalry, other factors also have a role to play. The spatial frequency composition of the gratings is one such factor which is consistent with all of the findings we report.

1 Introduction

Binocular rivalry is the term describing the alternating monocular suppression elicited by dichoptically viewing monocular stimuli which are sufficiently dissimilar that binocular correspondence fails. The phenomenology of rivalrous suppression is very compelling. Suprathreshold stimuli which would otherwise be clearly visible can become completely invisible for periods of several seconds or more. Indeed, during these phases, subjects cannot distinguish between the phenomenally absent stimulus and the physically absent stimulus. The intriguing nature of binocular rivalry, and the relative ease with which it can be induced, probably contributed to its being described earlier than many other perceptual phenomena. Dutour (1790) contributed early observations on binocular rivalry, and Wheatstone (1838) and later Breese (1909) both conducted systematic investigations. Despite the early description of the phenomenon, binocular rivalry is still not fully understood. A number of models have been proposed to account for binocular rivalry (Cogan 1987; Grossberg 1987; Lehky 1988; Wolfe 1986), with Blake's (1989) being the most comprehensive.

One curious aspect of binocular rivalry was reported by Liu et al (1992). Using dichoptically presented, orthogonal gratings, they found that the onset of alternating, rivalrous suppression could be delayed when low-contrast stimuli were used. During this period, they observed a stable, composite percept combining both monocular images which they termed a 'dichoptic plaid' (1992, page 1471). Increasingly long periods of these dichoptic composites were found as contrast was reduced. In a series of experiments, they investigated a number of other variables which were found to further retard the onset of binocular rivalry and ultimately arrived at a set of conditions which allowed stable, dichoptic plaids to be perceived for periods of up to 20 s or more. Contrast was found to be the prime determinant; luminance, spatial frequency, and waveform were also factors affecting the percept. When stable dichoptic plaids could be seen, their duration generally tended to be brief, although the stable dichoptic plaid seen for long periods at low contrasts differentiates it from the abnormal or 'false' fusion. False fusion is the pointwise summation of the monocular images carried out by the binocular system prior to the activation of the rivalry mechanism (Blake et al 1991). The phenomenon of 'false' fusion has been shown to be limited to very brief durations, typically of less than 150 ms, and its duration does not vary with changes in stimulus contrast (Wolfe 1983).

The present series of experiments also involves orthogonal gratings and examines the factors determining the perception of dichoptic plaids. Factors further to those examined by Liu et al (1992) are explored and are found to enhance the perception of dichoptic plaids. They are reported with the aim of broadening our understanding of the processes underlying binocular rivalry and factors which retard its onset.

2 Experiment 1: the effect of spatial frequency and contrast

Experiment 1 was intended first to validate our procedure and apparatus on two of the salient factors reported by Liu et al (1992): spatial frequency and contrast. A second aim was to manipulate spatial frequency while keeping aperture size constant. In order to control for the number of cycles seen in each condition, Liu et al (1992) reduced the size of the aperture as they increased spatial frequency. They argued that this may account for their observed spatial-frequency effects since rivalry may be inhibited in areas close to a fusible target (the aperture), and this inhibition would account for a greater proportion of small displays (which were the high-frequency ones) than large displays. By maintaining a constant aperture size we will thus be able to assess the effect of spatial frequency per se. In addition, we examine five levels of spatial frequency, whereas Liu et al (1992) compared only two.

2.1 *Method*

2.1.1 *Apparatus.* The stimuli were generated by a Macintosh IIci computer, displayed separately on two 12-inch Apple monochrome monitors and dichoptically presented to the subject in a tachistoscope by means of orthogonally oriented polaroid filters. These ensured that the image from each monitor was projected to only one eye. The programme generating the stimuli provided independent control over contrast, luminance, waveform, spatial frequency, and duty cycle. The stimuli remained on the monitors for the duration of a condition and LCD shutters (with a response latency specified to be approximately 25 ms) were used to control their presentation to the subject. A headrest built into the viewing aperture of the tachistoscope was used to minimise head movements and provided a comfortable viewing position.

2.1.2 *Stimuli.* The stimuli were two stationary, orthogonal luminance gratings always oriented ±45° with respect to vertical. Only square-wave gratings were used as Liu et al had already shown these stimuli to rival less than sine waves. The experiment involved five levels of (fundamental) spatial frequency (1, 2, 4, 6, and 9 cycles deg^{-1}) and contrast (5%, 15%, 30%, 55%, and 85%). As a result of Liu et al's (1992) finding that low levels of luminance allow greater contrast before inducing the onset of binocular rivalry, average luminance was relatively low at 6 cd m^{-2}. Circular apertures in the fields of the tachistoscope provided a viewing angle of 5° from a distance of 90 cm. As in Liu et al's (1992) experiment 4, the stimuli were presented for 500 ms and were otherwise occluded by the LCD shutters in the closed (opaque) position.

2.1.3 *Procedure.* Contrast and spatial frequency were varied in a 5×5 factorial design and there were ten trials in each of the twenty-five conditions. Subjects were instructed to report whether the gratings fused to form a plaid or whether they rivalled. Because the 500 ms stimulus duration was not long enough for the eyes to engage in the alternating suppression which characterises binocular rivalry, one of three percepts could be seen when the gratings did not fuse. Either the vertical or the horizontal grating only was visible, or the stimuli appeared as a piecemeal array of vertical and horizontal patches. Subjects were given a description of the possible percepts, and were shown patterns which were found in pilot work either to fuse almost always or not to fuse. Practice continued until subjects were satisfied they had established a reliable criterion for making the 'plaid' judgment and were familiar with the three, nonplaid percepts. The percentage of plaid judgments was the dependent variable. There was a pause between trials of at least 3 s when only the blank, opaque shutters were visible, and a 60 s pause after every ten trials when subjects could rest their eyes. No fixation point was used and the room was very dimly illuminated.

2.1.4 *Subjects.* Six relatively experienced psychophysical observers took part in the experiment. All were third-year psychology students participating as part of the requirements for an advanced psychophysics course. Prior to the experiment, subjects were screened for stereopsis by means of the Titmus test, and only those with excellent stereoacuity participated in the experiment. All subjects had normal vision or wore appropriate corrective lenses during testing.

2.2 *Results*

Both contrast and spatial frequency were significant as main effects, with $F_{3,15} = 17.024$ ($p < 0.0001$) and $F_{4,20} = 45.242$ ($p < 0.0001$), respectively. The interaction between these factors failed to reach significance ($p = 0.09$). It should be noted that the 5%-contrast level has been left out of the statistical analysis because it was subthreshold for several of the subjects at 6 and 9 cycles deg^{-1}. When these gratings were visible, they were always judged to be a plaid. Figure 1 is a plot of the results.

2.3 *Discussion*

The finding that the dichoptic plaid percept is reported more often at lower contrast levels and higher spatial frequencies is consistent with Liu et al's (1992) data. It also suggests that their results were a genuine effect of spatial frequency, and not an artifact

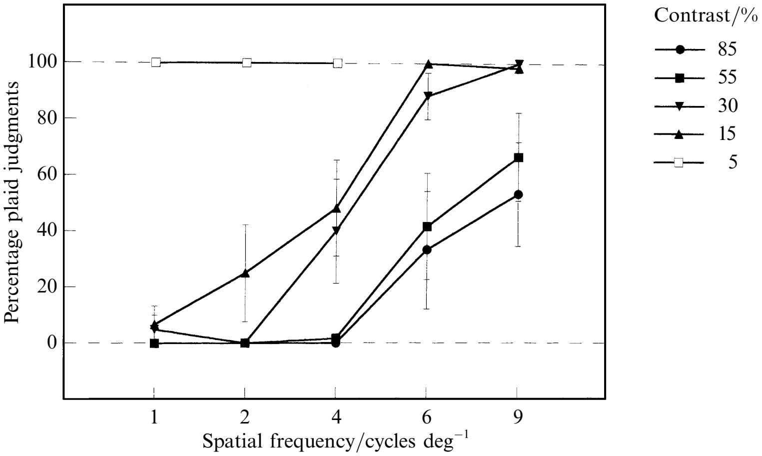

Figure 1. Percentage of 'plaid' judgments as a function of spatial frequency and contrast for experiment 1. Error bars represent ±1 standard error of the mean (the same convention is used for all of the following figures). Data points for the 5% contrast are not shown for the two highest spatial frequencies as the data were incomplete. These stimuli were reported to be subthreshold by several subjects, for at least some of the trials. Whenever they were seen, however, they were judged to be plaids.

of changing aperture size. Relating these data to other findings concerning binocular rivalry is instructive. Levelt (1965), for example, defined stimulus strength in a rivalry paradigm as being related to the amount of contrast and contour per unit area, with stronger stimuli having a propensity to engage in more rapid alternating suppression. This approach has effectively explained a variety of findings in binocular rivalry (Wade et al 1984), but is only partially consistent with these data. While we did find gratings of high contrast produced more rivalry judgments, Levelt's definition suggests that the reduced number of contours in the low-spatial-frequency conditions should produce more plaid judgments. Our data indicate the opposite relationship. The reason for this difference may be that Levelt's law relates to the rivalry process per se (ie the alternating suppression of monocular stimuli) whereas this experiment, and those by Liu et al (1992), concern a period of binocular fusion before the onset of bistable suppression.

If binocular fusion and binocular rivalry are separate phenomena, the mechanisms mediating binocular rivalry are likely to differ from those underlying binocular fusion prior to rivalry onset. A good deal of empirical evidence suggests that rivalrous suppression is carried out by low-level, monocular cortical channels exerting interocular, reciprocal inhibition (Blake 1989; Lehky 1988). In contrast, Liu et al (1992) proposed that the perception of dichoptic plaids arises from a binocular mechanism which carries out a pointwise spatial summation which is orientationally nonselective. If this were so, the spatial tuning of dichoptic plaid perception would not necessarily be predicted by data from rivalry experiments. However, complicating this distinction are recent findings indicating that activity in higher-level, binocular cortical areas correlates better with alternating perception in binocular rivalry than activity in lower cortical areas (Logothetis et al 1996; Sheinberg and Logothetis 1997). Data from Kitterle and Thomas (1980) support a distinction between the two phenomena. They examined the alternation rate of rivalling sine-wave gratings of various spatial frequencies and orientations. They report that alternation rate was maximal with orthogonal gratings at around 3–4 cycles $\deg^{-1}$, which is very close to the peak in the spatial-contrast-sensitivity function. The data from this experiment, however, show no indication of a similar function, with plaid judgments decreasing monotonically with spatial frequency.

If one assumes that the effects reported here relate to a threshold for activation of the binocular-rivalry process (Liu et al 1992), the data show clearly that the threshold level for its onset depends on spatial frequency and contrast. A potentially relevant finding is reported by Hollins (1980), who found that the completeness of binocular-rivalry suppression depends on spatial frequency and contrast, with suppression becoming more complete with decreasing spatial frequency and increasing contrast. Moreover, suppression completeness was found to increase with trial time up to 40 s. Thought of in these terms, the data reported here and those of Liu et al (1992) may be more indicative of minimised rivalry suppression rather than a failure to activate the process of binocular rivalry.

3 Experiment 2: the effect of duty cycle

In their experiment 5, Liu et al (1992) reported that changes to the harmonic structure of the gratings altered the contrast threshold for activation of binocular rivalry. Adding consecutive odd harmonics to the 0.5 cycle $\deg^{-1}$ sine-wave grating increased the likelihood of the dichoptic plaid percept, with square-wave gratings combining more than sine-wave gratings by a factor of about 2. In addition, removal of the fundamental frequency from the square-wave gratings led to even-higher dichoptic stability. Liu et al (1992) relate these results to physical differences between the structures of square-wave and sine-wave gratings, concluding that high spatial frequencies inhibit the rivalry process and thus low spatial frequencies stimulate its onset. However, it is possible that these waveform differences have perceptual consequences which go beyond the elementary encoding of the stimuli in various spatial frequency channels, and which may play a role in regulating rivalry onset. One perceptually prominent difference is the sharply defined changes in luminance seen in square-wave patterns. Potentially, these perceptual consequences could account for the differences in fusion threshold. Perhaps regions of equal luminance in the dichoptically combined image provide a temporary basis for fusion. The fact that these regions are larger, constant, and more clearly defined in square waves than in sine waves could then account for the superiority of fusion with square waves.

As a first step towards choosing between these possibilities, we varied the duty cycle (defined here as dark-bar width as a percentage of wavelength) of dichoptically presented square-wave gratings to reveal its effect on fusion. There were two reasons for doing so. The first is that it provides another means of varying the spatial frequency content of the gratings, since making square waves into rectangular waves involves adding even harmonics to the fundamental, in addition to the odd harmonics which are contained in a square-wave grating. According to Liu et al's (1992) interpretation, the increasing weight of the even harmonics as the gratings become increasingly rectilinear (ie as duty cycle moves away from 50%) should lead to increasing levels of dichoptic plaid perception, producing a U-shaped function. The second reason for varying duty cycle is that it can be used to alter the area of isoluminant overlap in the dichoptic image, and so provides a tool for examining the alternative possibility that this is a factor in retarding the onset of binocular rivalry. This alternative will be examined in detail in the following two experiments. In the present experiment, we measure the levels of dichoptic plaid perception with gratings of various duty cycles.

3.1 *Method*

All aspects of the apparatus and procedure were identical to those reported in experiment 1. Two levels of spatial frequency (2 and 6 cycles deg^{-1}) and contrast (15% and 85%) were combined with five levels of duty cycle (10%, 30%, 50%, 70%, and 90%), completing a $2 \times 2 \times 5$ factorial design. Six observers from the same subject pool took part.

3.2 *Results*

Duty cycle was a significant main effect ($F_{4,20} = 3.604$, $p < 0.05$) with plaid judgments increasing as duty cycle moved away from 50% (shown in figure 2, averaged across both levels of contrast). Contrast and spatial frequency were also significant main effects, with $F_{1,5} = 46.078$ ($p < 0.01$) and $F_{1,5} = 22.714$ ($p < 0.01$), respectively. Consistently with the previous experiment low contrast led to more plaid judgments, as did high spatial frequency. None of the two-way interactions or the three-way interaction was significant.

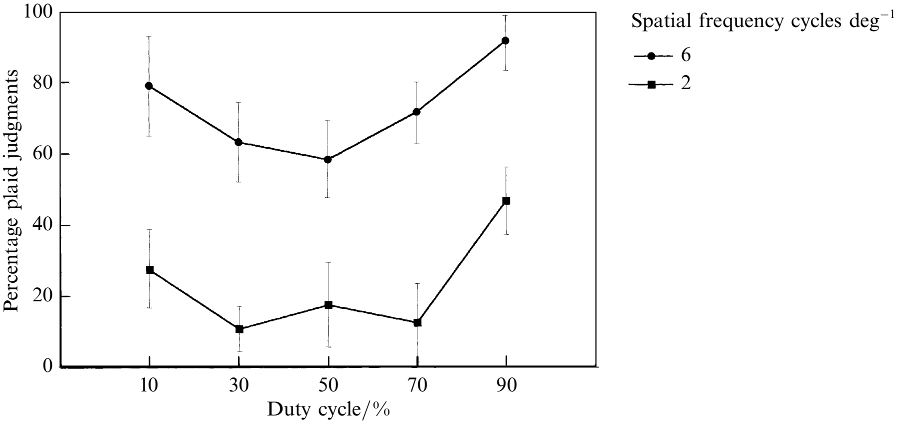

Figure 2. The interaction between duty cycle and spatial frequency from experiment 2, showing a clear main effect of spatial frequency and a U-shaped function for duty cycle.

3.3 *Discussion*

Apart from varying the harmonic composition of the grating waveforms, one consequence of manipulating duty cycle is that it affects average luminance. In this experiment, mean luminance increases as duty cycle decreases, so that for the data shown in figure 2 the mean luminance of the 10%-duty-cycle condition is greater than the mean luminance of the 90% condition by a factor of 2.33. With this in mind, there is a potential explanation in terms of Levelt's (1965) concept of stimulus strength, since higher values of duty cycle, being of lower luminance, will exhibit less frequent alternations of rivalrous suppression, and lower values of duty cycle will alternate more rapidly. In relation to this, Liu et al (1992) reported that mean luminance affected the fusion of dichoptically presented gratings, with lower levels of luminance favouring binocular fusion, although the sizes of their effects were relatively modest, given their large (log-scale) changes in luminance. This might explain why there is no striking effect of mean luminance in figure 2, although the average plaid judgment in the 90%-duty-cycle conditions (69.17%) is higher than the 10%-duty-cycle conditions (53.33%). In any event, both accounts would predict a monotonic function, rather than the U-shaped functions which we obtained, and so further explanation is called for.

As mentioned above, manipulating the duty cycle of rectilinear waveforms varies their harmonic composition and hence Fourier power spectra. It is well known that a square wave is composed of a fundamental frequency and each of its odd harmonics added with an amplitude inversely proportional to their frequency. A square wave is composed of a series of harmonics with frequencies (f, $3f$, $5f$, $7f$, ... nf) and corresponding amplitudes (1, 1/3, 1/5, 1/7, ... $1/n$). With rectangular waves, however, even harmonics are introduced into the synthesis, and their amplitude varies with changes in duty cycle. Indeed, as duty cycle approaches 0% or 100%, the power of the first few even harmonics approaches that of the fundamental (Campbell and Robson 1968). So, as with the various waveforms used by Liu et al (1992), our duty-cycle manipulations also involve the inclusion of higher harmonic frequencies. Moreover, the U-shaped pattern of results in figure 2 is consistent with the explanation offered by Liu et al (1992) that the inclusion of higher harmonics increases the perception of dichoptic plaids.

While the results of this experiment are consistent with an interpretation in terms of the Fourier spectrum of rectangular waves, there are other possible explanations of the duty-cycle effect which need to be tested. As mentioned in section 3, another factor which varies with changes in duty cycle is the size of the regions in the fused stimulus which receive congruous luminance input from the two eyes. This has the effect of rendering the dichoptic stimulus increasingly free of interocular conflict as duty cycle moves away from 50%, which would also lead to the prediction of a U-shaped function if it, and not spatial frequency composition, were the key variable determining the likelihood of perceiving a fused dichoptic plaid. This possibility is examined in the next experiment.

4 Experiment 3: the effect of the size of congruent luminance regions

When orthogonal square-wave gratings are presented dichoptically, half the area of the fused stimulus contains congruous luminance information. This occurs where dark (or light) vertical bars in one eye cross dark (or light) horizontal bars in the other. Equally, the other half of the dichoptic image contains incongruous luminance information, where dark bars overlap light bars, or vice versa. For a given spatial frequency, as the duty cycle changes, so does the size of these regions of luminance congruence, and, as duty cycle approaches 0% or 100%, the regions of congruent overlap increase in size, approaching 100% of the fused stimulus. It is not unlikely that whether the monocular images are dichoptically combined relates to the size of these areas of congruent luminance overlap. This is the implication of theories which suggest a low-level site for binocular rivalry (Mueller 1990) with interocular inhibition carried out by monocular neurons as the basis for rivalrous suppression (Blake 1989). If the size of the congruent regions of the dichoptic image were sufficiently large, then there would be monocular neurons in each eye which would receive binocularly congruent input. Accordingly, there would be a reduction in the number of monocular cells engaging in interocular suppression. This is another potential explanation of the U-shaped duty-cycle effect observed in experiment 2.

While the changes in duty cycle in experiment 2 did indeed alter the size of the areas of congruent overlap, these changes were confounded with the effects of spatial frequency composition. In the present experiment, we use two manipulations to decouple these factors. In experiment 3a, in order to test the effect of the total area of congruent luminance overlap, we factorially varied duty cycle and fundamental spatial frequency in a manner which produced a number of combinations with identical total areas of congruent overlap. The conditions with identical overlap are shown in table 1. Cells shaded in the same way expose the subject to the same total area of congruent luminance information. If this is the major determinant of the duty-cycle effect in experiment 2, then the conditions represented by similarly shaded cells should show almost equal fusion likelihoods.

Table 1. The factorial crossing of the stimulus conditions used in experiment 3. Cells with similar shading have identical total areas of congruent (and therefore incongruent) luminance information. If this is the prime determinant of fusion likelihood, then conditions shaded in the same way should produce similar percentages of plaid judgments. They did not (see figure 3).

Spatial frequency/ cycles deg^{-1}	Duty cycle/%			
	50	65	80	95
1.0	■	░	▓	□
1.29	░	■	░	▓
1.6	▓	░	■	░
1.9	□	▓	░	■

In experiment 3b, rather than manipulating the absolute size of the regions of congruent overlap, we consider the whole stimulus and the proportion containing congruent luminance information. Aperture size and fundamental spatial frequency are held constant while duty cycle is manipulated. If the duty cycle of both monocular patterns is matched, the proportion of congruent luminance information is restricted to a lower limit of 0.5 (when the gratings are each of 50% duty cycle) and a maximum approaching 1.0. To expand this range, we used grating pairs with both matched and *complementary* duty cycles, where complementary means that the lines in the gratings are equal in thickness, but the polarity of the contrast is reversed in one of the gratings. In this way, the proportion of congruent luminance information can be varied over a range approaching 0 – 1.0.

4.1 *Method*

All aspects of the apparatus and procedure were identical to those reported in experiments 1 and 2. Only orthogonally oriented, rectangular-wave stimuli were used, and all stimuli were presented at 15% contrast and oriented at $\pm 45^\circ$. In experiment 3a there were sixteen stimulus conditions, four spatial frequencies (1.0, 1.3, 1.6, and 1.9 cycles deg^{-1}) × four duty cycles (50%, 65%, 80%, and 95%). In experiment 3b the duty cycles of the matched gratings (and proportion congruent when combined) were 50% (0.5), 60% (0.52), 70% (0.58), 80% (0.68), and 90% (0.82), while those of complementary grating pairs were 60%/40% (0.48), 70%/30% (0.42), 80%/20% (0.32), and 90%/10% (0.18). In this way, the proportion of congruent luminance information is varied from 0.82 down to 0.18 in steps which, while not linearly spaced, are nonetheless symmetrically arranged around the midpoint of 0.5 The fundamental spatial frequency of the gratings was always 4 cycles deg^{-1}. Seven new subjects from the same pool took part in experiment 3a, and another six in experiment 3b.

4.2 *Results*

As is shown in figure 3a, the data from experiment 3a show a highly significant main effect of duty cycle ($F_{3,18} = 169.97$, $p < 0.0001$). The spatial-frequency effect was also marginally significant ($F_{3,18} = 3.44$, $p = 0.04$), as was the interaction between the factors ($F_{9,54} = 2.42$, $p = 0.022$), although both effects seem to be due to an unusually low percentage of plaid judgments in the 1.3 cycles deg^{-1} condition at the 80% duty cycle.

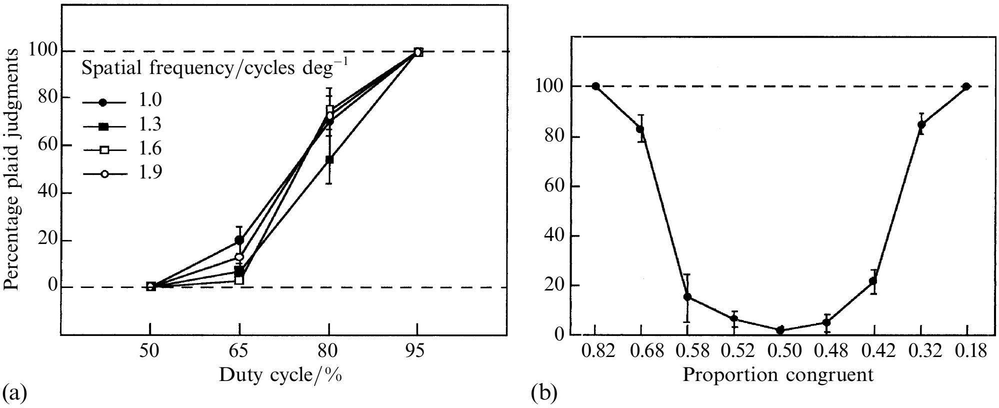

Figure 3. The results from experiment 3. (a) The interaction between duty cycle and spatial frequency. Across the ranges used, duty cycle has a much stronger and more consistent effect than spatial frequency. Importantly, conditions with matched total areas of luminance congruence (see table 1) do not show similar levels of rivalry. (b) The effect of the proportion of the dichoptic stimulus containing congruent luminance information on plaid judgments. For proportions higher than 0.5, orthogonally oriented but otherwise identical gratings were superimposed. For proportions lower than 0.5, gratings with thin dark lines were superimposed on complementary gratings with similarly thin light lines (see text for details). Plaid judgments are clearly influenced by duty-cycle composition, but clearly not by proportion congruent.

The data from experiment 3b (see figure 3b) were analysed by using a one-way ANOVA and revealed a significant effect of proportion congruent ($F_{8,40} = 86.93$, $p = 0.0001$). Importantly, it can be seen from figure 3b that this effect is not monotonic: the effect is almost perfectly symmetrical about 0.5. This pattern of results is contrary to predictions based on the monotonic changes in the proportion of congruent luminance overlap and therefore suggests that it does not determine fusion likelihood. Rather, these data strongly support the interpretation that the presence of increasingly powerful even harmonics as the proportion of congruent luminance moves away from 0.5 is determining the perception of dichoptic plaids in this experiment. Further, the striking symmetry in the data indicates that this effect operates in a manner which is independent of the contrast polarity of the gratings.

4.3 *Discussion*

The results of experiment 3a reconfirm that duty cycle is a powerful determinant of dichoptic fusion. That this effect is much stronger than the spatial-frequency effect reflects the narrow range over which spatial frequency was manipulated (necessitated by the constraint of achieving equal congruence). If the size of congruent luminance overlap was the main determinant of the duty-cycle effect seen in experiment 2, as hypothesised, then there would be a strong interaction between duty cycle and spatial frequency. Although an interaction between these factors was observed, it is a small effect which is not of great empirical relevance. It is more meaningful to consider the data from the main diagonal in table 1, which all have the same area of congruent overlap, and so should produce similar levels of dichoptic plaid perception according to the hypothesis. Clearly, they do not: each level of duty cycle produces a cluster of datum points which do not overlap at all with data from any of the other duty cycles. Thus, the duty-cycle effect is not due to changes in the size of the congruent luminance regions.

The second hypothesis we tested was whether the overall proportion of the stimulus containing congruent luminance information plays a role in dichoptic fusion, rather than the size of these areas. The results of experiment 3b show convincingly that the proportion of congruent luminance is not an important determinant of binocular fusion. The fact that the two highest levels of fusion were obtained in the conditions at the extremes of the luminance-congruence range illustrates this point. Taken in conjunction with experiment 3a, these results rule out luminance overlap as an explanation of the changing levels of binocular fusion as duty cycle is manipulated. There are two remaining effects of varying the duty cycle of the to-be-fused gratings which could have a causal role to play. The first is that increasing the duty cycle of the gratings results in a reduction in the proportion of the fused stimulus containing conflicting *contour* information, and the second is the spatial frequency composition of rectangular waves, as discussed previously. If the density of conflicting contour information is a determinant of the duty-cycle effect, then the symmetrical results of experiment 3b (which are discussed in relation to the spatial-frequency hypothesis, below) suggest that the polarity of the conflicting edges is not important. This potential explanation of the effect is examined in experiment 4.

Before testing the contour-conflict explanation, it is important to note that all of the results so far reported are consistent with the fact that changing the duty cycle of a grating changes its spatial frequency composition, and that the addition of high spatial frequencies encourages fusion. In this respect, the most telling aspect of the data is the near-perfect symmetry in figure 3b, reflecting the symmetrical increase in the power of the even harmonics as duty cycle moves away from 0.5. The pairs of luminance-congruence conditions which are equally spaced about 0.5 all have identical harmonic power spectra, and differ only in terms of their phase. Specifically, the left-eye and right-eye gratings contain harmonics which are in phase in the 0.82 condition but are 180° out of phase in the 0.18 condition, as they are in all of the conditions involving gratings with opposite contrast polarities. In terms of the spatial-frequency hypothesis, the fact that these conditions yield equivalent levels of dichoptic plaid perception suggests that the mechanism responsible for the fusion process is not sensitive to conflicting phase information in the two monocular images.

5 Experiment 4: the effect of contour intersection

Changing the duty cycle of dichoptically presented gratings not only affects the regions of congruent luminance (experiment 3), it also affects the amount of conflicting contour information in the dichoptic stimulus. Consider a dichoptic stimulus composed of orthogonal gratings of 90% duty cycle. Most of the stimulus is comprised of large, constant-luminance intersections where the large dark regions of the gratings overlap. These contain no contour information at all and so do not provide a basis for binocular rivalry. The stimulus also contains smaller regions where the thin portions of one grating are set against the large portions of the other. Again, these conditions provide no basis for binocular rivalry because contours seen against a background of uniform luminance remain constantly visible (Blake 1977). However, in the smallest regions of the dichoptic stimulus (0.18 in this case), the thin regions of the gratings intersect. Here two orthogonally oriented thin lines are present: the classical conditions for binocular rivalry (Breese 1909; Levelt 1965). The proportion of the stimulus satisfying these conditions varies as a function of duty cycle, so that a random sample of an image is less likely to find contour conflict with gratings of 90% (or 10%) duty cycle than with gratings of 50% duty cycle. Thus, if these intersections containing conflicting contour information are crucial to the onset of binocular rivalry (Kaufman 1963), a potential explanation of the duty-cycle effect in experiment 2 arises. Simply, the low proportion of contour conflict in gratings of high or low duty cycle may retard or even prevent the onset of rivalrous suppression, and thus account for the higher levels of fused, dichoptic plaids.

The most direct way to test this proposal is to remove these conflicting regions from the stimulus altogether. In this experiment, we manipulate contour conflict by using four patterns with different kinds of contour intersection (figure 4). If the presence of contour conflict is an important determinant of binocular rivalry then the straightforward prediction is that rivalry should be more likely in the display containing contour conflict (figure 4a) than in the displays which do not (figures 4b, 4c, and 4d). Pilot observations suggested that the conflict-free stimuli would strongly encourage fusion. To prevent the number of plaid percepts reaching a ceiling, we changed the stimulus parameters to encourage rivalry and lower the baseline number of plaid judgments so that any effects would be revealed.

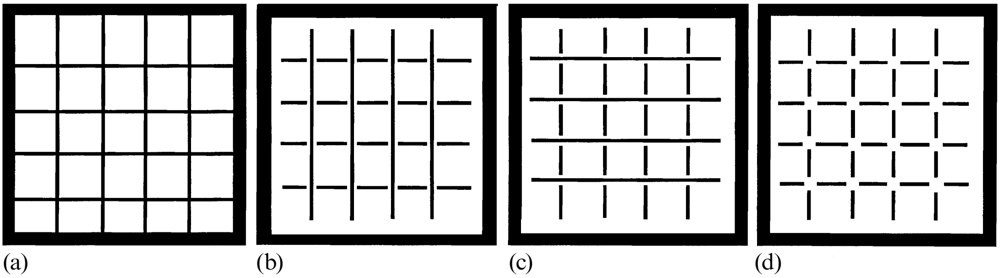

Figure 4. Representations of the stimuli used in experiment 4. The stimuli presented were very similar to those shown, except that the left-eye and right-eye views have been superimposed in this figure to show how fusion results in contour overlap only in the stimulus shown in (a). The stimulus configurations depicted are fused versions of (a) Hfull/Vfull, (b) Hgap/Vfull, (c) Hfull/Vgap, (d) Hgap/Vgap. This experiment also contained control conditions in which stimuli like those depicted were presented to one eye and an unfilled black square (fusion frame) was presented to the other. This never led to rivalry.

5.1 *Method*

5.1.1 *Apparatus.* The stimuli were generated by a Power Macintosh 7200 computer, and displayed on a single 14-inch Apple high-resolution RGB monitor. The two halves of the dichoptic stimulus were fused with a prism stereoscope mounted 20 cm in front of the monitor. The experiment was controlled by means of PsyScope 1.1.1 (Cohen et al 1993).

5.1.2 *Stimuli.* The stimuli were like those in figure 4. To encourage rivalry in the conflict-free conditions, average luminance was increased from 6 cd m^{-2} to 91 cd m^{-2}, contrast was increased to 94%, and exposure time was increased from 500 ms to 1500 ms. The stimuli were 5.5 cm across and subtended 15 deg at the viewing distance of 20 cm (the stereoscope magnified the images slightly). The horizontal full/vertical full (Hfull/Vfull) condition (figure 4a) was composed of orthogonal gratings, each with a duty cycle of 5% and a spatial frequency of 1 cycle cm^{-1} (or 0.366 cycle deg^{-1}). Pilot observations were used to determine the size of the gaps in the gapped lines (conditions shown in figures 4b, 4c, and 4d), since variations in binocular convergence could cause the monocular images to move relative to each other in the horizontal dimension. This would result in unwanted contour overlap if the gaps were very small (shown in figure 4d and especially in figure 4b). With fusion frames around the stimuli to minimise vergence movements, a gap size of 0.2 cm (0.54 deg) was as small as it could be without resulting in dichoptic contour overlap. Although relative shifting of the images is less likely in the vertical dimension, it can occur as a consequence of hyperphoria or hypophoria or owing to head tilt. For these reasons, the same gap size was used for the vertical gapped lines and a headrest was used to avoid head tilt. As well as the four stimulus arrangements shown in figure 4, we had control stimuli in which the left-eye and right-eye stimuli were combined and presented to one eye (in each of the ways depicted in figure 4), with only mean luminance surrounded by the square fusion frame in the other eye. This was done to compare the binocular rivalry obtained in the experimental conditions with baseline rates of monocular rivalry occurring in the control conditions.

5.1.3 *Procedure.* The four dichoptic arrangements depicted in figure 4 plus each of their monoptic controls made eight stimulus configurations. Counterbalancing for eye of presentation made a total of sixteen conditions, and the left-eye/right-eye reversals were later pooled and converted to percentages. Subjects completed entire random orders of stimuli ten times with a delay of 1 s between stimuli. Since the presentation of a plaid was only possible in the condition shown in figure 4a, subjects were instructed to report whether any part of the pattern disappeared during the exposure period. There were four types of response categories: 'neither' (the pattern remained completely visible), 'horizontal' (only horizontal contours disappeared), 'vertical' (only vertical contours disappeared), or 'both' (horizontal and vertical contours disappeared). There were two rest breaks programmed into the experiment.

5.1.4 *Subjects.* Eight first-year psychology students from the University of Wollongong served as subjects for nominal course credit. Subjects were screened for stereopsis by using the Titmus test, and only those with excellent stereoacuity participated. All subjects had normal vision or wore appropriate corrective lenses during testing.

5.2 *Results*

Since the data are not independent (eg ten 'neither' judgments in one condition determine a zero for the others), they were analysed within each response category separately in a series of 2 × 2 within-subjects factorial ANOVAs (vertical lines—gapped or full × horizontal lines—gapped or full). The data are shown in figure 5 by response category for each stimulus type. The monoptic data are not included in the analyses as all subjects judged the patterns as 'neither' for all trials, indicating that no binocular or monocular rivalry occurred when all contour information was presented to one eye.

The ANOVA for the 'neither' responses is shown in the first category of figure 5. Horizontal line type approached significance ($F_{1,7} = 5.12$, $p = 0.058$), while the main effect of vertical line type was significant ($F_{1,7} = 55.30$, $p = 0.001$). These factors also interacted significantly ($F_{1,7} = 8.80$, $p = 0.021$). This pattern of results is consistent with the hypothesis that, overall, 'neither' responses will be more likely in the three conditions without intersections, and specifically, most likely when both horizontal and vertical lines are gapped (Hgap/Vgap). Predictably, 'neither' responses are least likely when both horizontal and vertical lines are unbroken (Hfull/Vfull). Against our predictions, the Hgap/Vfull condition produced rivalry as often as the Hfull/Vfull condition. This probably resulted from vergence eye movements producing unwanted contour overlap.

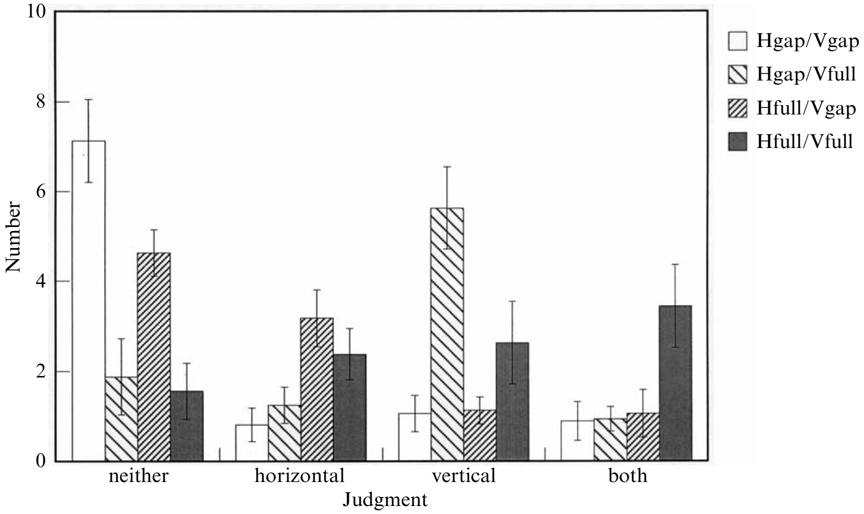

Figure 5. The data (mean number disappearing) recorded in each of the response categories in experiment 4. A response in the first category ('neither') means that both gratings were observed in their entirety. Responses in the 'neither' category, therefore, indicate an absence of binocular rivalry. A response in the other categories indicates that some part of the stimulus was suppressed by binocular rivalry, either the 'vertical' grating, the 'horizontal' one, or 'both'. For all categories, the maximum mean number of responses for any stimulus in any category is ten. For details of conditions, see figure 4.

The other three categories in figure 5 are informative about the distribution of responses when rivalry did occur. The data for the 'both' response are low in all conditions except Hfull/Vfull, almost perfectly reflecting the pattern expected if the absence of contour intersections inhibited binocular rivalry. Despite this, there was no significant interaction on this data set ($F_{1,7} = 2.44$, $p = 0.16$), although the main effects of horizontal line type ($F_{1,7} = 13.23$, $p = 0.008$) and vertical line type ($F_{1,7} = 5.98$, $p = 0.04$) were significant.

The ANOVA for the 'vertical' response did not yield a significant main effect of horizontal line type ($F_{1,7} = 3.41$), but the main effect of vertical line type ($F_{1,7} = 15.87$, $p = 0.005$) and the interaction ($F_{1,7} = 7.43$, $p = 0.03$) were significant. The significant main effect and interaction are attributable to the highest response occurring in the Hgap condition, meaning that full vertical lines alone are suppressed more often when superimposed on gapped horizontal lines. This is not surprising given that vergence eye movements would cause contour overlap. The surprising discovery is that rivalry leads to full lines disappearing more frequently than gapped lines. The horizontal lines were quite unlikely to disappear in such conditions.

Analysis of the 'horizontal' responses produced only a significant main effect of horizontal line type (more full than gapped horizontal lines disappeared; $F_{1,7} = 8.68$, $p = 0.022$). Vertical line type ($F_{1,7} = 0.132$) and the interaction ($F_{1,7} = 2.27$) were not significant. As in the 'vertical' response, when rivalry did occur, it was likely to be the full horizontal lines which disappeared rather than the gapped ones.

5.3 *Discussion*

The overall pattern of results agrees well with the predictions made from the assumption that rivalry is primarily produced by locally conflicting contour information in the two eyes. The order of conditions within the 'neither' response category (no rivalry reported) indicates this. When both contours are gapped (Hgap/Vgap), 'neither' responses are greatest, and they are least when both lines are continuous (Hfull/Vfull). Also as expected, the two conditions in which one of the lines is gapped fall between these conditions. The only apparent inconsistency is that the Hgap condition (Hgap/Vfull) is considerably lower than the Vgap condition (Hfull/Vgap). This is most likely due to vergence errors and vergence eye movements causing the horizontal gapped line to become dichoptically continuous. If so, this most likely occurred with the naive subjects, since the gap size in the stimuli was carefully piloted on the authors beforehand.

Further support for our predictions comes from the rather low response levels in the three rivalry categories in figure 5. In each of the 'horizontal', 'vertical', and 'both' categories, the number of responses totals about 30%, which is surprising if one considers that the stimulus parameters in this experiment were designed to encourage a strongly rivalrous response when and if it occurred. In contrast, rivalry is much more common than nonrivalry for the Hfull/Vfull condition (85% vs 15%), and is spread fairly evenly among the response categories. Thus, when local contour conflict is removed, the likelihood of binocular rivalry occurring is markedly reduced. Further explanation, however, is needed to fully account for these data because of clear differences between the Hgap/Vgap and Hfull/Vgap conditions. In these conditions, contour overlap is minimal regardless of vergence eye movements, yet there are still fewer 'neither' responses in the Hfull/Vgap condition than in the Hgap/Vgap condition. Thus, full horizontal lines are sometimes suppressed despite not intersecting with the vertical (gapped) lines.

Examining the 'horizontal' and 'vertical' responses for the Hgap/Vfull and Hfull/Vgap conditions reveals a noteworthy finding: the occurrence of rivalry caused the suppression of the full lines more than the gapped lines. While gapped lines might intuitively be thought of as weaker stimuli than continuous lines, the inverse is more likely to be true. This follows from the well-established empirical findings that strong stimuli predominate over weaker ones (Breese 1909; Levelt 1965). On these grounds, the suppression of the continuous lines by gapped lines should reflect the greater strength of the gapped lines. The reason for this may be that the gapped lines contain more Fourier energy at non-orthogonal orientations than the continuous lines. Gapped lines contain a great deal of broadband energy at all orientations which is related to the line terminators at each end of the short line segments, whereas the continuous lines only contain energy orthogonal to the orientation of the line.

Evidence against contour conflict being the sole cause of rivalry is that rivalry sometimes occurred in the Hgap/Vgap condition, despite the absence of any dichoptic intersections. Given the very high luminance and contrast of these contours and the longer presentation times, rivalry is remarkably low in this condition (the 'neither' response is 72%). This figure is even more impressive given the stricter criterion used in this experiment. In the previous experiments, subjects had only two response choices (plaid vs rivalry) and so in reporting the dominant percept they would have occasionally responded "plaid" when a small degree of rivalry may have been present. Despite these unfavourable conditions, the Hgap/Vgap stimulus produced no rivalry in just over 72% of trials. Nonetheless, reports of rivalry in the remaining 28% of trials suggest that local contour conflict is not the only cause of rivalry since this would predict 100% 'neither' responses. Evidently, while rivalry onset is strongly related to contour conflict, it can sometimes occur in the absence of such conflict. The reason for this is probably related to the small size of the intersections and gaps in the stimuli. This would mean that the area surrounding the gap would also be imaged on the receptive field of a given orientation-selective cell and influence its response, with the surrounding area having more impact with increasing retinal eccentricity. This is consistent with findings showing that rivalrous suppression occurs in zones whose size reflects the variation in receptive field size with spatial frequency and eccentricity (Blake et al 1992; O'Shea et al 1997).

6 General discussion

The experiments described in this paper have produced a number of potentially important findings. We have shown that the spatial-frequency effect discovered by Liu et al (1992) is a genuine effect, not due to the confounding of aperture size in their experiment. We have also replicated their contrast effect with a different measure. In experiment 2 we manipulated duty cycle and found a strong effect of this variable. The higher or lower the duty cycle of a pattern (the thinner the lines became), the more likely it was to be judged a fused plaid. The results of experiment 3 ruled out any simple explanation of this effect in terms of the amount or proportion of the dichoptic stimulus which contained congruent luminance information, and the results of experiment 4 showed that a large part of the duty-cycle effect can probably be explained in terms of the reduced density of contour conflict as duty cycle increases or decreases, since removing the intersections greatly reduces the likelihood of rivalry occurring.

The original reason for manipulating duty cycle was to attempt to decide whether the spatial-frequency effect of Liu et al (1992) and experiment 1 was due to spatial frequency per se, or to other factors associated with varying line thickness. In experiments 1 – 3 these two accounts make identical predictions, because altering the duty cycle of a grating also alters its spatial frequency composition, as has already been discussed. The results of experiment 4 strongly suggest that the duty-cycle effect could be mediated in part by a reduction in the density of conflicting contour information, since removing such information dramatically reduces the likelihood of binocular rivalry occurring. However, the results of experiment 4 also leave room for the spatial frequency spectrum of the orthogonal gratings to operate as a causal mechanism.

If we consider Liu et al's (1992) original spatial-frequency effects, which we have shown not to be artifacts of aperture size in experiment 1, then we have clear evidence that contour conflict is not the whole story. If it were, then we would predict a spatial-frequency effect which is the exact opposite of the one which was obtained. Increasing the spatial frequency of the monocular gratings obviously *increases* the number of places in the dichoptic image containing conflicting contour information, and yet this leads to fewer rivalry judgments. It is ironic that the manipulations which were designed to probe the spatial-frequency effect (varying duty cycle) have in fact produced an explanatory mechanism which explicitly cannot account for the spatial-frequency effect. Instead, it seems likely that contour conflict and spatial frequency have independent effects on binocular rivalry, and that the residual rivalry in the Hgap/Vgap condition in experiment 4 is due to the presence of conflicting high-contrast, high-luminance, high-spatial-frequency Fourier components in the displays.

The current findings, and those of Liu et al (1992), provide important information about the conditions under which the binocular-rivalry process is not activated (or is only weakly activated), which may help guide future theorising about the mechanisms underlying stereopsis and rivalry. Despite this, the nature of the results obtained makes it difficult to draw out any firm implications for existing theories of rivalry.

Previous researchers have, for example, concluded that binocular rivalry (like stereopsis) is a function of the magnocellular pathway (Livingstone 1996; Livingstone and Hubel 1987), although others have doubted this claim (Blake 1989; Tyler 1990). The fact that rivalry is less likely at high spatial frequencies could be used as support for a magnocellular contribution to producing rivalry, since the magnocellular pathway is not very sensitive to high spatial frequencies. However, the fact that rivalry is also less likely at low contrast is inconsistent with this conclusion, because low contrasts favour the magnocellular over the parvocellular pathway. Any simple pathway account would need to predict that rivalry would be least likely at high spatial frequencies *and* high contrast. Conversely, it is not clear that any existing neurophysiological theory of stereopsis or of rivalry would predict rivalry to be most likely at low spatial frequency and high contrast.

Similarly, the results of experiment 4 could be seen as being in accord with the views of Logothetis et al (1996), but they are not wholly supportive. On the basis of the fact that rapidly interchanging the monocular stimuli in a binocularly rivalrous display has little effect on the *perceptual* alternations occurring, Logothetis et al suggest that binocular rivalry is the consequence of a dynamic resolution of ambiguous stimulation, and that presenting different orientations to each eye is just a convenient way of creating ambiguity. They are suggesting, in other words, that binocular rivalry is caused by the same kinds of perceptual mechanisms that produce monocular rivalry, or perceptual oscillation in displays with ambiguous depth relationships (Necker cubes, or ambiguous figure/ground displays).

The reason our results could be seen as consistent with this general position is that when we removed the areas of orientation conflict from the fused image, rivalry was dramatically reduced (even at high contrast), despite the fact that the monocular views, as a whole, were inconsistent. This is further evidence that stimulus conflict, not ocular conflict, is the driving force of rivalry. The reason our result is not entirely consistent with Logothetis et al's suggestion is that it, in accord with the piecemeal nature of rivalry in general, seems to be a consequence of *local* ambiguity. The perceptual oscillation underlying displays with ambiguous depth relationships, on the other hand, is caused by global ambiguity. A Necker cube could be the two-dimensional projection of either of two real three-dimensional cubes, but this is only apparent—and is only ambiguous—if the *whole* two-dimensional projection is taken into account. In contrast, our results show that binocular rivalry can be strongly suppressed if the small areas of locally conflicting (ambiguous?) information are removed, despite a more global inconsistency.

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