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Influence of spatial frequency, luminance, and duration on binocular rivalry and abnormal fusion of briefly presented dichoptic stimuli

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Abstract. Orthogonal gratings, presented dichoptically, do not fuse into a single percept. Parts of each are seen while other parts are suppressed in an unstable perception (binocular rivalry). However, it has been previously noted that, if the gratings are briefly flashed, they will appear to fuse into a plaid or checkerboard pattern. Three experiments are reported which have been designed to define more clearly the spatial and temporal parameters of this effect in the hope that this would lead to better understanding of the normal mechanisms of dominance and suppression. Stimuli appear fused if flashed for less than 150 ms. The effect is independent of substantial changes in spatial frequency and luminance. Single flashes that appear fused when presented in isolation produce rivalry if separated by intervals less than about 150 ms. Intervals greater than 150 ms produce continued abnormal fusion. Possible mechanisms are discussed.

1 Introduction

When each eye views a different pattern, two varieties of visual perception are logically possible. Each time dissimilar images fall on corresponding points in the two eyes, the images could be seen to fuse into some composite figure or one image could be suppressed and the other perceived at each location where a mismatch occurs. In virtually all cases the visual system uses the second strategy. If, for example, a pattern of high-contrast vertical lines is presented to the left eye while horizontal lines are presented to the right, some regions of the visual field will be perceived as containing vertical lines while some regions will contain horizontal lines. No fusion of vertical and horizontal will be seen. The percept is unstable (eg Helmholtz 1909/1962; Breese 1899). "At any one moment all of one image or all of the other, or some piecemeal mosaic of the two is seen but not all of both simultaneously" (Blake 1977). This apparent competition for perceptual dominance is known as binocular rivalry (Breese 1899).

Over the last 70 years, an interesting violation of the normal rules has been repeatedly observed. When briefly presented, normally rivalrous stimuli appear to fuse abnormally into a composite pattern. Perhaps the earliest reference is in Hering (1920/1964). In his discussion of rivalry, Hering mentions in passing that "when I ... exposed the image [orthogonal dichoptic lines] for only a fraction of a second, ... I always saw both systems of lines with equal clarity" (page 261). Kaufman (1963), Bower and Haley (1964), Goldstein (1970), Wade (1973), and Anderson et al (1978) have also described the effect. Further, the existence of the effect is implicit in Schiller and Wiener (1963). In spite of the numerous references to the effect in the literature, it is not well described or understood. Anderson et al (1978), in the most detailed report, find considerable variation from subject to subject and from trial to trial as the temporal parameters are varied. Both Anderson et al and Goldstein (1970) find some apparent fusion with flash durations as long as 500 ms. Others seem to observe rivalry under these conditions. Parameters such as spatial frequency and luminance are known to influence the time course of many phenomena. They have not been systematically studied in this context.

A better understanding of this phenomenon would be useful because, rather than being just another curiosity in the already complicated field of interocular interactions, the phenomenon can be of use in increasing our understanding of interocular suppression. This paper has three purposes: (i) to describe the temporal properties of the phenomenon more precisely; (ii) to study the effects of manipulating luminance and spatial frequency; and (iii) to determine if flash durations that fail to produce rivalry when presented alone, will produce rivalry if presented sequentially in a flickering display.

2 Experiment 1: The basic phenomenon

2.1 *Apparatus*

Subjects viewed high-contrast (>95%) square-wave gratings of 3.8 cycles deg^{-1}. Stimuli were presented in a Scientific Prototype six-channel tachistoscope with three independent channels per eye. Timers were accurate to less than 1 ms and the rise and decay to half-brightness times of the lamps were also rated at less than 1 ms. Vertical stimuli were presented to the left eye, horizontal to the right. Mean luminance was 2.6 log units (with luminance measured in cd m^{-2}). Stimuli were circular fields subtending 2.6 deg. They were presented briefly in synchrony to each eye. Duration of presentation was varied from 10 to 1000 ms. In this experiment the vertical was always presented to the left eye and horizontal to the right eye. Informal observations and the results of other experiments indicate that results would be no different if the orientations were reversed.

2.2 *Subjects*

Nine subjects were tested. Subjects were between the ages of 18 and 30 years. All had or were corrected to 20/20 acuity and all had stereopsis as assessed by the ability to see large-disparity random-dot stereograms. Seven subjects were naive with respect to this experiment; two (JMW and SG) were not.

2.3 *Methods*

To quantify subjective impressions of rivalry and fusion, subjects were taught a rating scale where a rating of 5 denoted the fused perception and 0 denoted rivalry. To instruct the subjects, orthogonal dichoptic gratings were continuously presented, producing rivalry. With the comparatively large stimulus fields used here, rivalry, when it occurred, was not unitary. Some parts of the field would appear to contain vertical contours while other contained horizontal. Subjects were instructed to give a rating of 0 to this type of patchwork perception. Subjects were told that any trial that appeared to be entirely vertical or horizontal was also to be rated 0. Subjects were told to pay particular attention to the intersections of vertical and horizontal bars. Conditions rated as 0 did not show complete intersections between vertical and horizontal contours. In conditions meriting a 5, subjects were told that all possible intersections would be clearly visible and could be described as looking like plaids or checkerboards. Again, since the fields were large, it was possible to have some parts of the field apparently fused while other regions showed clear rivalry. Such conditions were to be given intermediate ratings with the rating dependent on the relative sizes of the apparently fused and apparently rivalrous regions. Any small region of the field appeared to be either fused or rivalrous. The subjects were rating the overall appearance of the stimulus. Most subjects learned to use the rating scale without difficulty.

On each trial, subjects viewed very dim fixation points to aid convergence. The experimenter informed the subject of an upcoming trial and presented the stimuli. The subject rated the stimuli on the 0–5 scale. If the subject required a second presentation, it was given. Repeat presentations were quite rare. Seven trials were run at each of ten stimulus durations (10–1000 ms). Trials were collected in blocks of ten with each duration being presented once before any duration was presented again. Order of presentation was random across durations. The first two ratings at each duration were discarded as practice.

2.4 *Results*

Under conditions of continuous viewing, the stimuli induced strong rivalry. Long flashes were perceived as single frames taken from continuous rivalry and were usually rated 0 or 1. When presented for durations of under 100 ms, the orthogonal gratings usually appeared to fuse into a crosshatched pattern and were usually rated 4 or 5. Naive individuals, asked to describe a 50 ms flash, routinely used terms such as 'plaid' or 'checkerboard'. Many were surprised to find that the 'checkerboard' was not present in both eyes. The transition from clearly rivalrous to clearly fused appearance occurred between 100 and 200 ms flash durations, with some individual trials appearing fused and some rivalrous.

Results for each of the nine subjects are presented in figure 1. Plotted points represent the mean of five ratings. Clearly, for most subjects, at durations of 100 ms or less the flashes appeared to be predominantly plaid. At durations longer than 400 ms they were almost invariably rivalrous. It seems most likely that subject EL misunderstood the task as she gave ratings of about 4 to 1000 ms flashes that invariably appeared rivalrous to all other subjects[1].

2.5 *Discussion*

As in the studies cited above, normally rivalrous, dichoptic stimuli were seen as fused or superimposed when briefly presented. In the most extensive previous study (Anderson et al 1978) much was made of the fairly large differences between subjects. In that regard, it is interesting to note how similar the results are for eight of the nine subjects in the present study. The reasons for the difference are not obvious but probably lie in the differences in our methods. Anderson et al used verbal reports and drawings of stimulus appearance. The rating-scale method used here seems to eliminate some of the variability. Further, Anderson et al flashed gratings without changing mean luminance, while in the present experiment it was dark between trials. When the methods of this experiment are used, little or no rivalry is seen with stimuli flashed for less than 150 ms and little or no apparent fusion is seen with durations greater than 150 ms.

Possible sources of noise in this experiment include poor convergence and unstable fixation. If convergence were not accurate, the dichoptic stimuli would not be perfectly superimposed. A percept having vertical stripes on one side and horizontal on the other would result. Such a percept would be rated at less than 5. If a subject was not fixating and was making an eye movement during stimulus presentation, it would tend to blur the grating orthogonal to the direction of the movement. The resulting percept would be dominated by the other grating and could be rated at less than 5. These factors could only reduce the likelihood that a stimulus pair would be labelled as fused. Thus, the abnormal fusion of normally rivalrous stimuli cannot be an artifact of such factors.

[1]One of the dangers in an experiment involving subjective rating-scale methods is that the experimenter could bias the results in the expected direction (eg by using subtle, even unconscious versions of "Are you sure that looks fused?"). To avoid this trap, seven of the subjects in experiment 1 were tested by an inexperienced undergraduate research aide. Obviously, the experiment still works but, in this case, we run the risk that a subject's mistaken notion of the task will go undetected. EL was probably rating something like the relative visibility of vertical and horizontal and finding it to be a constant of about 50% at all flash durations. It is possible that she was a highly unusual subject who did not experience normal rivalry. Unfortunately, the end of the term precluded follow-up testing.

One factor might lead to spurious reports of fusion. Perhaps the short flashes are so short that subjects are uncertain as to what they have seen. Long flashes certainly appear rivalrous. Subjects might rate the short flashes as fused in an effort to use the entire rating scale. Three observations render this unlikely:

(i) The data are very consistent across subjects. It is unlikely that all subjects would adopt such a strategy in the same way.

(ii) The short flashes were not, in fact, particularly hard to see or rate. They tended to look like short, fused flashes.

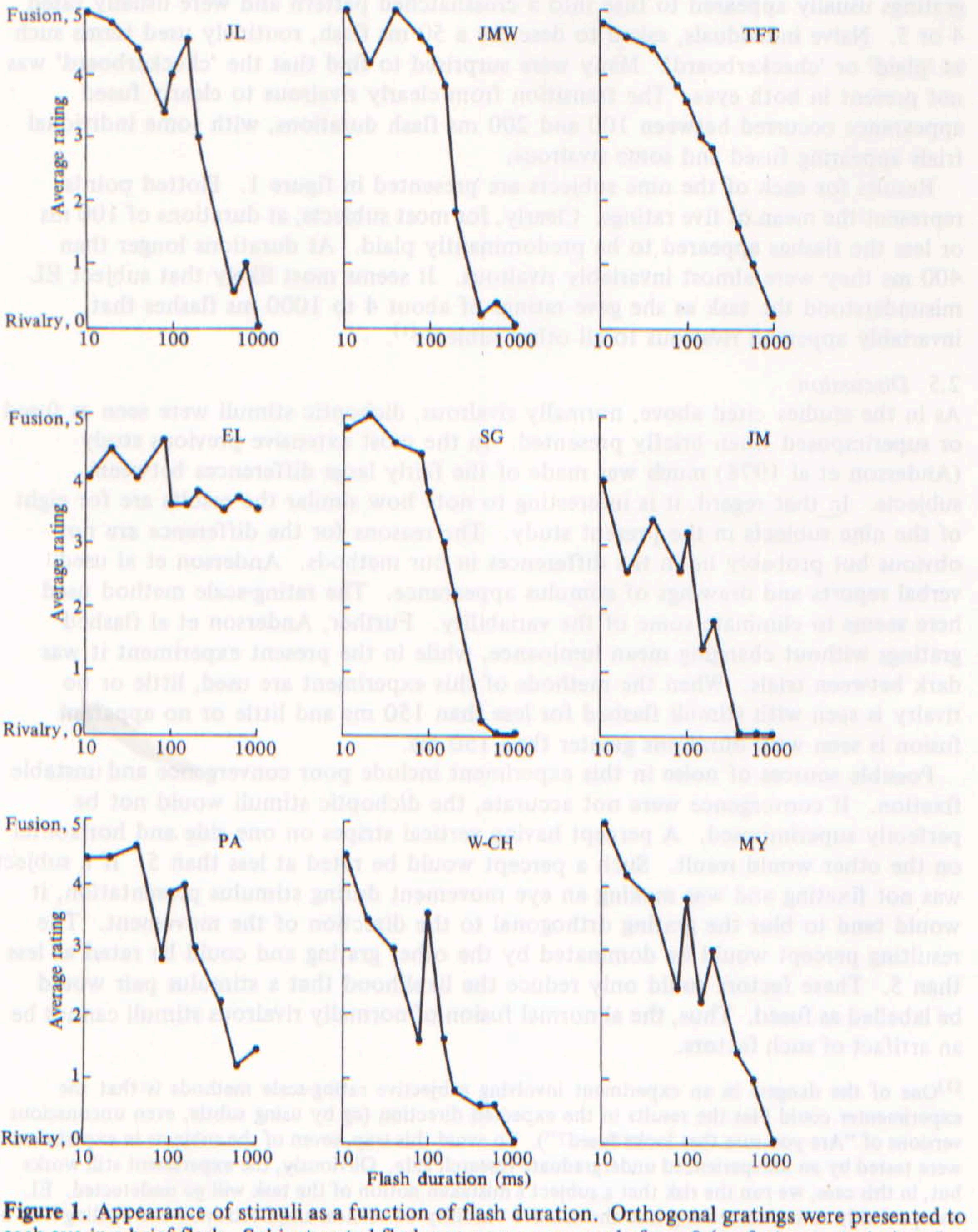

Figure 1. Appearance of stimuli as a function of flash duration. Orthogonal gratings were presented to each eye in a brief flash. Subjects rated flash appearance on a scale from 0 (no fusion = rivalry) to 5 (cross-hatched pattern). Short flashes (<150 ms) appeared to be fused. Each point is the mean of five ratings.

(iii) In experiment 3 certain flickering stimuli continued to appear fused even though they were present for 2 s. In sum, for the stimulus conditions described in experiment 1, subjects consistently reported that orthogonal dichoptic gratings appeared to fuse. In the next experiment, effects of changes in the spatial parameters of the pattern are examined.

3 Experiment 2: Effects of spatial frequency and mean luminance

There has been considerable debate as to whether the mechanisms of dominance and suppression are sensitive to changes in the spatial frequency of rivalrous stimuli. Certainly the temporal characteristics of other aspects of vision are affected by changes in these parameters. For example, perceptual reaction times change systematically with changes in luminance (Roufs 1974) and spatial frequency (Harwerth and Levi 1978). In rivalry studies, the question is not entirely resolved. Change in luminance leads to a change in the alternation rate in binocular rivalry (eg Kaplan and Metlay 1964). There seems to be less of an effect of spatial frequency (Kitterle and Thomas 1980) though Wade (1975) and Fahle (1982) find some effect. To the contrary, results of Blake and Fox (1974) suggest that these parameters have little effect on the depth of suppression. In experiment 2, spatial frequency and luminance of the dichoptic stimuli were varied. Perhaps surprisingly, these parameters do not affect the temporal properties of the transition from abnormally fused to rivalrous perceptions.

3.1 *Apparatus and stimuli*

The apparatus was identical to that used in experiment 1. There were six conditions: three different spatial frequencies were tested with luminance and contrast held constant, and three luminances were tested with spatial frequency and contrast held constant. In varying spatial frequency, square-wave gratings of 8.5 and 16.4 cycles deg^{-1} were used in addition to the 3.8 cycles deg^{-1} gratings. All gratings were of greater than 95% contrast and their mean luminance was 2.6 log units. To vary the mean luminance, neutral density filters were placed in front of the gratings. Filters of 10% and 1% transmittance were used, yielding mean luminances of 1.6 and 0.6 log units in addition to that of 2.6 log units. When the luminance was varied, spatial frequency was held at 3.8 cycles deg^{-1}.

3.2 *Subjects*

Three subjects were tested in this experiment. Two were experimenters; one (CC) was naive. All had or were corrected to 20/20 acuity and all had stereopsis.

3.3 *Methods*

The six conditions were run in separate sessions. The methods used were the same as in experiment 1. Subjects were asked to maintain similar criteria from session to session. This was not difficult, though different combinations of frequency and luminance did, of course, look different.

3.4 *Results*

Figure 2 presents data from two subjects: JMW's data for the effect of spatial frequency and CC's results for luminance. There is no significant or systematic effect of either frequency or luminance. Results for all subjects were qualitatively similar.

3.5 *Discussion*

The results of experiment 2 were somewhat surprising since informal observation strongly suggested that there would be an effect of both spatial frequency and luminance. Lower luminances and higher spatial frequencies seemed more prone to abnormal fusion. However, when the results were examined systematically, no effect could be found. The explanation may lie in a form of a practice effect. Even for practiced observers, the first trials in a session are quite variable in appearance and the abnormal fusion is less compelling. This is particularly true for high-luminance low-frequency patterns. Thus, initially, a low-luminance high-frequency grating may, indeed, appear to fuse more readily, but when performance has stabilized, no difference is found.

Given this 'learning' effect, it could be that the entire effect is an artifact of the subject learning to say what the experimenter wants to hear. This hypothesis can be discounted. Much of the data in experiment 1 were collected by a naive experimenter from naive subjects (see, again, footnote 1). Further, in none of the experiments did the subjects know the duration of a given trial, making it very unlikely that all subjects could produce similar functions by artifact. We have no explanation of this learning effect, though it seems phenomenologically similar to the learning effect seen with random-dot stereograms. Stereograms are often easier to see after a number of presentations (Julesz 1971; Frisby and Clatworthy 1974).

The effect of contrast was not tested because of equipment limitations. It might be expected that contrast would have an effect as there are a number of reports that very-low-contrast orthogonal dichoptic gratings can appear fused even when viewed continuously (eg Abadi 1973).

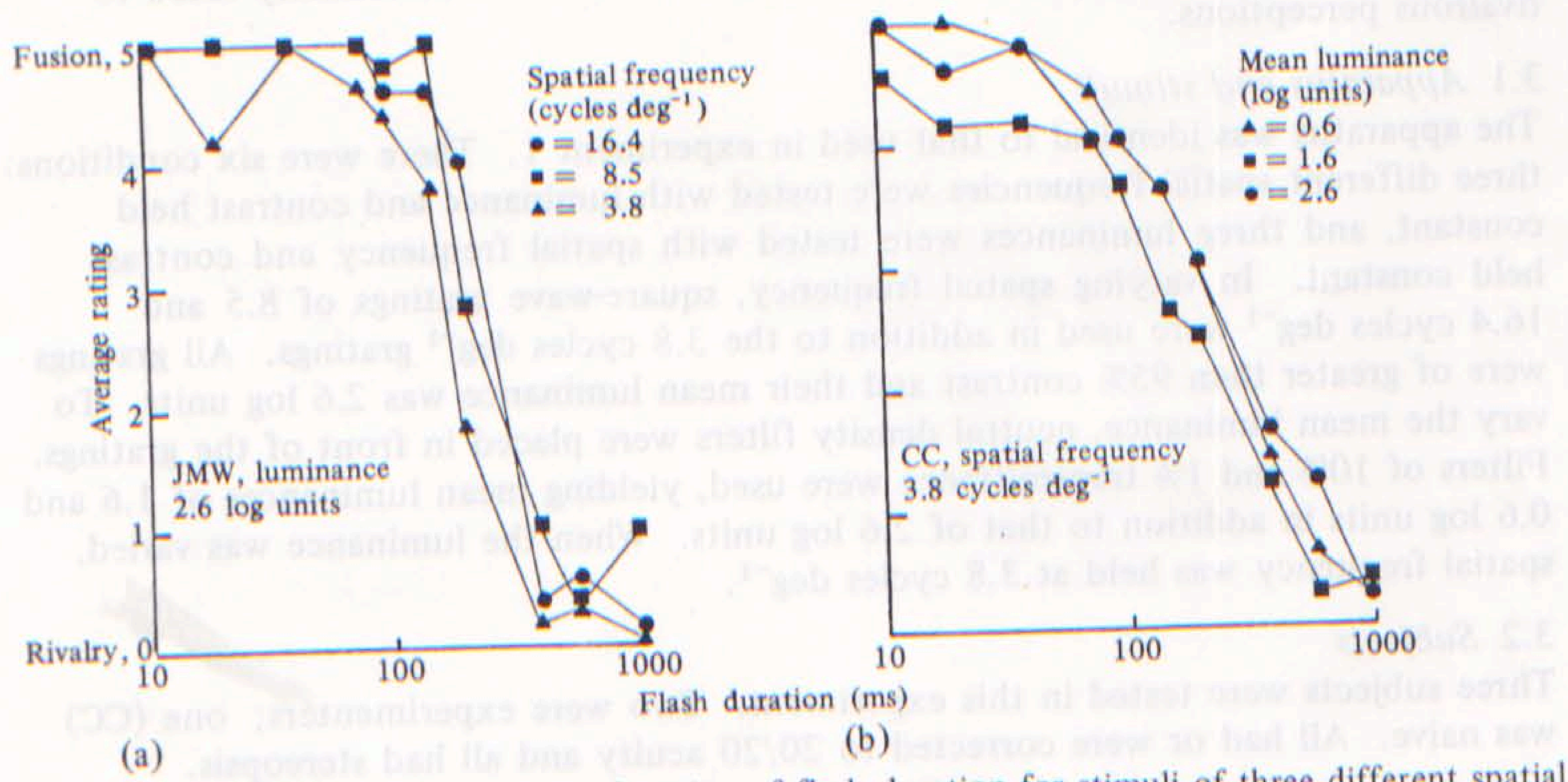

Figure 2. Appearance of stimuli as a function of flash duration for stimuli of three different spatial frequencies (a) and three different mean luminances (b). Neither variable seems to have a major effect on the temporal characteristics of abnormal fusion or rivalry. Luminance measured in cd m^{-2}.

4 Experiment 3: Temporal summation in binocular rivalry

A 10 ms flash of dichoptic orthogonal gratings will almost always appear abnormally fused. What if more than one flash is used? More than 150 ms of stimulation are needed to produce rivalry in a single flash. If the stimulus is removed before that time, no rivalry will be seen. Can stimuli of duration shorter than 100–200 ms summate over time to produce rivalry? If so, how wide is the window of temporal summation in rivalry? Experimental results, presented below, show that successive flashes will produce rivalry if separated by less than 100–200 ms independently of the length of the individual flashes and of the luminance or spatial frequency of the stimuli.

4.1 *Apparatus*
The apparatus was similar to that used in the previous experiments. However, in this experiment stimuli were flickered rather than presented in a single brief flash. As the results will show, it proves to be more convenient to refer to interstimulus interval (ISI), the period from the offset of one flash to the onset of the next, than to use the actual flicker rate. We examined the effects of luminance, spatial frequency, and flash duration on temporal summation in rivalry. In all sessions ISI was varied from 20 to 800 ms in nine steps. In individual sessions the effects of three variables were examined. With a flash duration of 10 ms and a mean luminance of 2.6 log units, spatial frequencies of 3.8, 8.5, and 16.4 cycles deg^{-1} were tested. With a flash duration of 10 ms and a spatial frequency of 3.8 cycles deg^{-1}, mean luminances of 0.6, 1.6, and 2.6 log units were tested. Finally, with a spatial frequency 3.8 cycles deg^{-1} and a mean luminance of 2.6 log units, three flash durations were tested (10, 50, and 100 ms). When presented in isolation, a single flash of 10 or 50 ms almost always appears to be fused. A single flash of 100 ms usually appears to be fused.

4.2 *Subjects*
In addition to the author, two naive subjects were tested. One had been a subject in experiment 1. All subjects had or were corrected to 20/20 acuity and all had stereopsis.

4.3 *Method*
Seven different sessions were run with each subject. The methods were similar to those used in experiments 1 and 2. As before, subjects used a 0–5 scale to rate the appearance of the stimuli. Instead of a single flash, however, a flickering stimulus was presented on each trial and remained visible until the subject had rated it (<10 s). Flash duration, spatial frequency, and mean luminance were all held constant during a single session. Only ISI was varied. Subjects were asked to maintain similar criteria for ratings across sessions and reported no difficulty in doing so.

4.4 *Results*
Phenomenologically, the most striking aspect of this experiment was the ability to produce a continuously visible plaid with stimuli that normally produce strong rivalry.

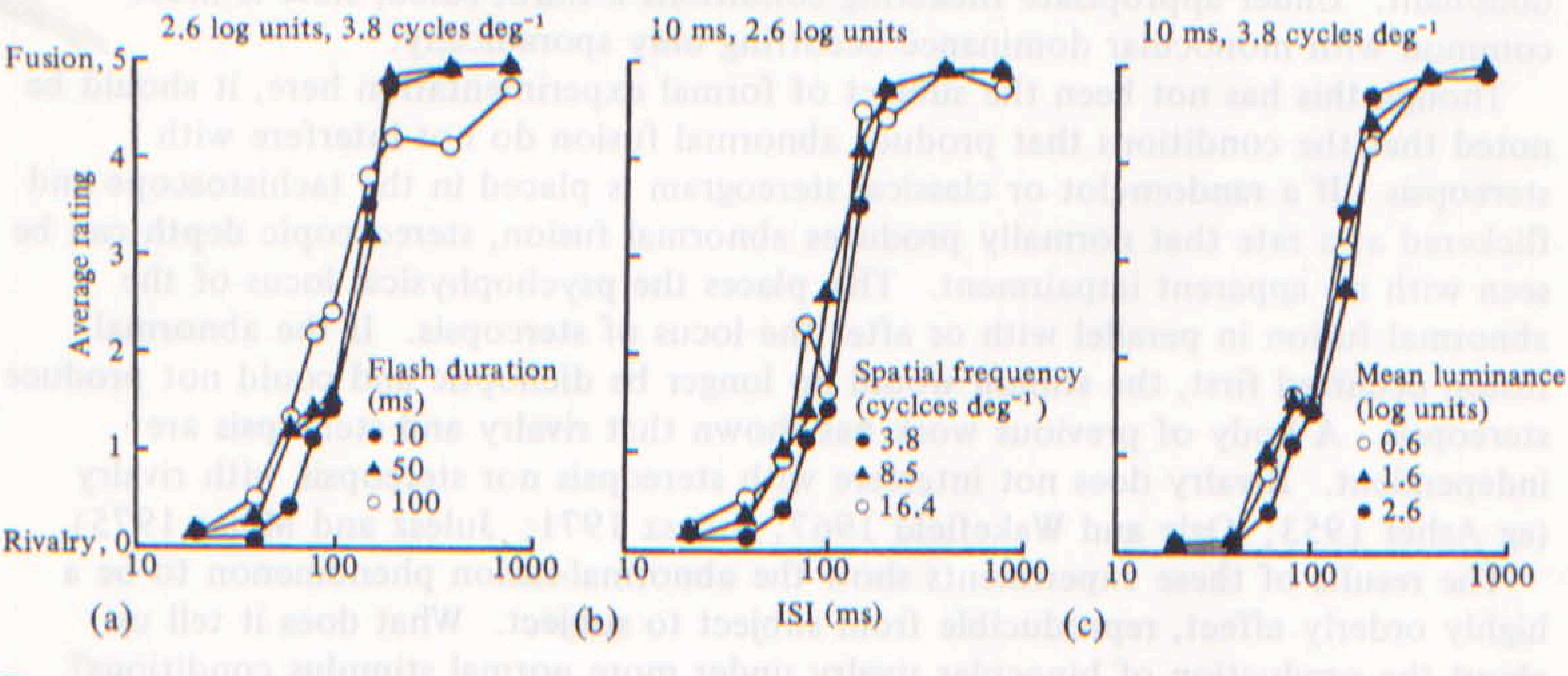

Figure 3. Appearance of stimuli in flickering stimuli. In each panel, stimulus appearance is shown as a function of ISI. In (a) each curve represents a different flash duration. In (b) each curve represents a different spatial frequency. Finally (c) shows the effect of changing mean luminance. There is no significant effect of flash duration, spatial frequency, or luminance. It should be noted that the same data for the 10 ms flash, 2.6 log unit, 3.8 cycles deg^{-1} condition have been replotted in (a), (b), and (c). The condition was run only once for each subject. Luminance measured in cd m^{-2}.

10 ms flashes, presented at a rate of 6 Hz give the appearance of a continuously visible plaid that is illuminated by a flickering light source. Results of experiment 3 are shown in figure 3. Figures 1 and 2 have shown what the data of individual subjects looks like. In figure 3, results are averaged for all three subjects. Note that the steepness of the averaged functions suggests that all three subjects made very similar ratings.

For short ISIs (higher temporal frequencies) successive flashes that appear abnormally fused when presented individually, summate to produce rivalry. For ISIs greater than 150 ms, the string of flashes does not produce rivalry. Figure 3a shows this to be independent of the length of the individual flashes. Figure 3b indicates that there is no effect of spatial frequency over a two-octave range. Finally, figure 3c demonstrates that there is no effect of mean luminance over a 0.6–2.6 log unit range. The single critical variable is the interval between the offset of one flash and the onset of the next.

4.5 *Discussion*

A simple rule can be extracted from experiments 1, 2, and 3. Orthogonal dichoptic gratings will appear fused if they are presented in flashes of less than 150 ms separated by ISIs of more than 150 ms. A curious corollary is that no flicker with a duty cycle greater than 50% will produce abnormal fusion. A prediction from this result would be that dichoptic stimuli will give rise to rivalry even if they are asynchronously presented to each eye. O'Shea (personal communication) has shown that this is the case for relatively short ISIs. For long ISIs, the alternation between successive stimuli can be perceived and true rivalry vanishes.

O'Shea has also examined synchronous presentation under conditions that produced abnormal fusion in experiment 3. He reported rivalry but with a very slow alternation rate. In experiment 3, subjects viewed a few seconds of flickering dichoptic stimuli and rated their appearance. O'Shea's subjects viewed the stimuli for a prolonged period of time and reported on phases of dominance and suppression. In looking at abnormally fused patterns for extended periods of time, it is true that one or the other orientation may fade or disappear for a brief period of time. However, this does not represent a return to normal rivalry. In normal rivalry there are two predominant states for any location in the field: left-eye dominant and right-eye dominant. Under appropriate flickering conditions a third, fused, state is most common with monocular dominance occurring only sporadically.

Though this has not been the subject of formal experimentation here, it should be noted that the conditions that produce abnormal fusion do not interfere with stereopsis. If a random-dot or classical stereogram is placed in the tachistoscope and flickered at a rate that normally produces abnormal fusion, stereoscopic depth can be seen with no apparent impairment. This places the psychophysical locus of the abnormal fusion in parallel with or after the locus of stereopsis. If the abnormal fusion occurred first, the stimuli would no longer be dichoptic and could not produce stereopsis. A body of previous work has shown that rivalry and stereopsis are independent. Rivalry does not interfere with stereopsis nor stereopsis with rivalry (eg Asher 1953; Ogle and Wakefield 1967; Julesz 1971; Julesz and Miller 1975).

The results of these experiments show the abnormal-fusion phenomenon to be a highly orderly effect, reproducible from subject to subject. What does it tell us about the production of binocular rivalry under more normal stimulus conditions? The most obvious hypothesis would be that the patterns of dominance and suppression that underly the experience of rivalry require some time to develop. On the basis of results presented here, one could argue that the rivalry mechanism has a 'rise time' of about 150 ms. Before the stimuli have been present for 150 ms, both monocular stimuli can get past the level of binocular rivalry and are perceived, apparently fused.

One version of this model would state that a single monocular stimulus of less than 150 ms duration cannot participate in rivalry. This version is contradicted by the following observation. A subject views a vertical grating with, say, the right eye. The left eye is not stimulated. Blake and Camisa (1978) have shown that this condition is equivalent to the condition where the stimulated right eye is dominant over the unstimulated left eye. During normal rivalry, thresholds are elevated in one eye when stimuli presented to that eye are suppressed by stimuli presented to corresponding points of the other eye. Blake and Camisa found the same threshold elevation in an unstimulated eye contralateral to a stimulated eye, so the rivalry mechanism appears to be 'on' during monocular stimulation and the stimulated eye is dominant.

A brief stimulus is now flashed to the previously unstimulated left eye. There are four possible outcomes. If the brief flash cannot participate in rivalry, then either (i) it will not be seen or (ii) it will be seen as abnormally fused with the other grating. If the brief flash can participate in rivalry it could rival with the other stimulus (iii), or it could suppress the other stimulus (iv), or it could be suppressed and not be seen [(i), again]. The result is (iv). The brief flash suppresses the sustained stimulus in the contralateral eye over a wide range of stimulus conditions. Apparently, a flash of less than 150 ms duration can take part in rivalry if the rivalry mechanism is already 'on'. The details of this paradigm and a discussion of why a brief flash completely suppresses a dominant flash in the other eye is the burden of another paper (Wolfe 1984).

For the purposes of this paper, these observations combined with the results of the experiment reported here suggest that the rivalry mechanism requires 150 ms of stimulation of either eye to become active. Briefer flashes are processed differently either by default or by design. Research on sustained and transient processes in vision suggests that the processing of brief stimuli may, indeed, be the task of special mechanisms (eg Enroth-Cugell and Robson 1966; Enoch 1978). The relationship of the results reported here to other distinctions between the processing of brief and longer-duration stimuli remains to be examined. Further research on this phenomenon should help to define the flow of information in the human binocular visual system.

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