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# The temporal course of suppression during binocular rivalry

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**Abstract.** Orthogonally oriented sinusoidal luminance gratings were dichoptically presented to the observers' left and right eyes. During the subsequent binocular rivalry, a small target was briefly presented (4AFC) to probe the strength of interocular suppression at various temporal latencies. Both stationary and moving rivalrous patterns were investigated. The purpose of experiment 1 was to compare the temporal characteristics of stationary and motion rivalry (0 and  $1.2 \text{ deg s}^{-1}$ ), while that of experiment 2 was to examine rivalry suppression for higher speeds (2 and  $4 \text{ deg s}^{-1}$ ). In all cases, it was found that the strength of suppression remained essentially constant throughout a single phase of binocular rivalry. The results of the investigation also revealed that moving rivalrous patterns lead to greater magnitudes of interocular suppression than static patterns. Despite these differences in the strength of suppression, the results of both experiments show that the temporal characteristics of motion and static rivalry are essentially

## 1 Introduction

It is a fact of nature that human observers have two eyes that are separated horizontally a few centimeters apart from each other. Because of this separation, the two eyes receive slightly different perspective views of the external environment. When we fixate one object at a given position in depth, the retinal images of other objects often fall outside of Panum's fusional area (Howard and Rogers 1995). We, however, do not typically perceive these double images in normal visual situations. Instead, we see an apparently single world even though our binocular fusional area is limited. One reason the world appears single is that retinal image discrepancies that are too large to be fused are suppressed or inhibited. The phenomenon of binocular rivalry is a good example of such interocular suppression (Blake 1989; Breese 1899; Levelt 1968; Wheatstone 1838).

When very dissimilar stimuli are presented dichoptically, observers will usually experience binocular rivalry: they will perceive only the right-eye stimulus or only the left-eye stimulus, or a piecemeal mosaic containing individual parts that come exclusively from either the left-eye or the right-eye stimulus. Previous research has shown that the amount of exclusive rivalry (no piecemeal mosaic) depends upon many factors, such as the size of rivalry stimuli, their retinal eccentricity, spatial frequency, or contrast (Blake et al 1992; Hollins 1980; Liu and Schor 1994; O'Shea et al 1997). It also depends upon the speed of the patterns (for moving stimuli), or whether there are other adjacent stimuli near the rivalrous patterns (Blake et al 1998; Fukuda and Blake 1992; Wade et al 1984).

When one of the rivalry stimuli is exclusively suppressed, the detection of a change introduced to the suppressed view is significantly impaired. It has been shown that the blockage of information processing during suppression occurs not only when a probe target is briefly superimposed on the suppressed pattern (Blake and Camisa 1979; Fox and Check 1966; Wales and Fox 1970), but also in situations where the suppressed stimulus itself undergoes some change (Blake and Fox 1974; Fox and Check 1968). This research indicates that rivalry suppression occurs nonselectively, regardless of the particular content of the rivalrous patterns themselves.

The strength of suppression can be evaluated by comparing the detectability of a probe stimulus which is presented during the suppressed phase of rivalry with that presented during the dominant phase. Fox and Check (1972) attempted to determine whether the strength of rivalry suppression changes over time during a single phase of binocular rivalry, or whether it remains the same. In their experiment, they presented black and white concentric circles to one of the observers' eyes and an achromatic negative pattern to the other eye. After the onset of rivalry, one of four alphabet letters was presented briefly, during either the dominant or suppressed phase. The observers' task was to identify the letter. The probe letters were presented at one of three (early, middle, or late) temporal latencies during a single phase of rivalry suppression. They found that the strength of suppression did not change over time, but remained constant until the next alternation between the left-eye and right-eye views.

The findings of Fox and Check (1972) are interesting. It is possible, however, that their particular choice of rivalry stimuli might have led to results that are unrepresentative of binocular rivalry in general, because their stimuli could produce not only binocular rivalry, but binocular luster (Helmholtz 1867/1962, page 512) as well. In addition, the study of Fox and Check, however suggestive, is limited to static situations—they used only stationary rivalrous patterns. It is possible that moving rivalrous stimuli might have different suppressive effects than stationary patterns, since different visual subsystems appear to process moving and stationary stimuli (eg Maunsell and Van Essen 1983; Merigan and Maunsell 1993). A number of earlier psychophysical studies also suggest that possibility. For example, over 100 years ago, Breese (1899) presented diagonally oriented black lines superimposed on a red background to one eye and orthogonally oriented lines superimposed on a green background to the other eye. The lines on the red field moved during observation, while the ones presented against the green background remained stationary. He found that the moving lines of the red field remained visible nearly all of the time, although the perceived field color itself alternated between red and green. In other words, even when the static lines belonging to the green field were dominant, the orthogonally oriented moving lines were also visible—the moving lines were not suppressed although the red background color was. This clearly suggested that moving and stationary rivalrous stimuli are processed differently. More recent studies have also shown that moving stimuli dominate over static stimuli during rivalry (Blake et al 1985, 1998; Wade et al 1984).

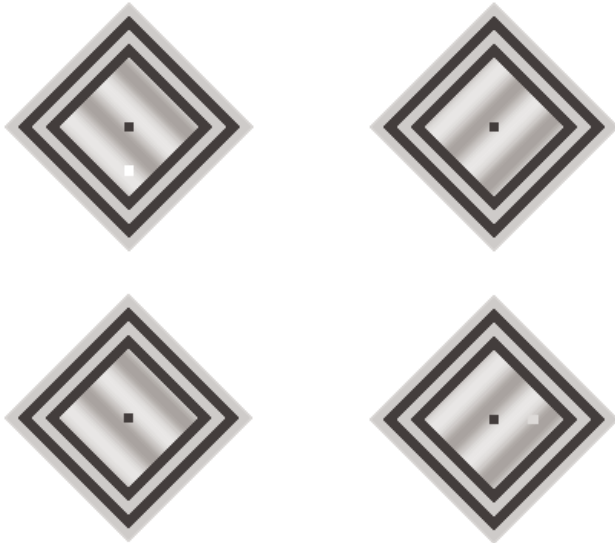
The purpose of this study is to thoroughly examine the temporal course of rivalry suppression for moving rivalrous patterns. Orthogonally oriented sinusoidal luminance gratings were used as rivalry stimuli. In experiment 1, we compared the temporal course of suppression during motion rivalry with the rivalry that occurs during static presentations. Blake et al (1998, see their figure 1c) showed that there is an optimal speed (around  $1.2 \text{ deg s}^{-1}$ ) that produces a maximum amount of exclusive visibility of each eye's view during rivalry. Therefore, we adopted that speed ( $1.2 \text{ deg s}^{-1}$ ) for the moving rivalry condition. In experiment 2, we used faster moving stimuli. Since we used small rivalrous stimuli ( $1.4 \text{ deg}$  width) to promote exclusive alternation (eg see O'Shea et al 1997), the maximum possible speed of the moving gratings that still preserved the perception of coherent motion was  $4.0 \text{ deg s}^{-1}$ . Therefore the motion speeds in the second experiment were set to 2 and  $4 \text{ deg s}^{-1}$ .

## 2 Experiment 1

### 2.1 Method

**2.1.1 Observers.** Two male and two female observers participated in the experiment. Two of them (HFN and JB) were authors and two others (AKH and SRR) were naïve to the purpose of the experiment. All observers had normal or corrected-to-normal vision and good stereopsis.

**2.1.2 Apparatus and stimulus displays.** Sinusoidal luminance gratings (figure 1) were generated by an Apple Power Macintosh 8500/120 and displayed on an Apple Multiple Scan 720 Display with a resolution of  $1024 \times 768$  pixels. The monitor was placed at a viewing distance of 114.6 cm. The presentation of the stimulus displays was accelerated by an Xclaim 3D graphics accelerator board (ATI Technologies, Inc).



**Figure 1.** An example of the binocular rivalry stimuli used in experiments 1 and 2. The sinusoidal grating at an orientation of  $45^\circ$  clockwise (CW) from vertical was presented to an observer's right eye, while the left eye received the counterclockwise (CCW) grating. The small black square in the middle of the stimulus presented to each eye served as a fixation marker. A probe square was presented for 100 ms at one of four possible positions within one of the rivalrous gratings when the observer's view of that grating was either exclusively dominant or suppressed.

Different orientations of the gratings [ $45^\circ$  clockwise (CW) or counterclockwise (CCW) from vertical] were shown to each eye separately by a mirror haploscope. There were two types of gratings: moving (ie translating in a direction perpendicular to the orientation of the grating) and static. The speed of the moving gratings was  $1.2 \text{ deg s}^{-1}$ . The contrast and the spatial frequency of the gratings were set at 50% and 2 cycles  $\text{deg}^{-1}$ , respectively. The individual frames of the apparent-motion sequences were updated at a rate of 50 Hz (ie every 20 ms). For static presentations, the phase of each sinusoidal rivalry stimulus was determined randomly on each trial. The sides of each of the diamond-shaped rivalry stimuli subtended 1 deg. The total height and width of the rivalry stimuli were therefore 1.4 deg. Two diamond-shaped gray contours surrounded each rivalry stimulus (0.1 deg width) and allowed the observers to maintain appropriate vergence. A small black square served as a fixation marker, and was located at the center of each rivalrous grating (width and height: 0.1 deg). A square probe which subtended 0.1 deg on each side was briefly presented at one of four possible locations within the rivalrous pattern (top, bottom, right, or left) in either the dominant-eye or the suppressed-eye view. The background surrounding the rivalry stimuli was black. The experiment was conducted in a dimly lit room under photopic conditions.

**2.1.3 Procedure.** If a probe spot of a particular fixed intensity had been used, its detectability would have depended upon the luminance of that part of the grating that it happened to be superimposed upon, which would have varied over time in the moving rivalrous conditions and across trials in the static conditions owing to the random phase of the gratings on each trial. Therefore we varied the brightness of the probe

depending upon the phase of the grating at the time and location where the probe appeared. More specifically, the probe was presented at a luminance that was a fixed increment from the background luminance of the grating that it was placed against. The magnitude of the luminance increment was determined individually for each observer so that the probe was detectable with an accuracy of 75%–80% under non-rivalry conditions where identically oriented gratings were shown to the observers' left and right eyes. Separate increments were determined for static and moving gratings. In these preliminary non-rivalry sessions, the observers were required to detect the location of the probe (left, right, up, down) at probe onset, which occurred 20 ms after the start of each trial (this probe latency was also used as one of the four latencies in the rivalry conditions, as described below).

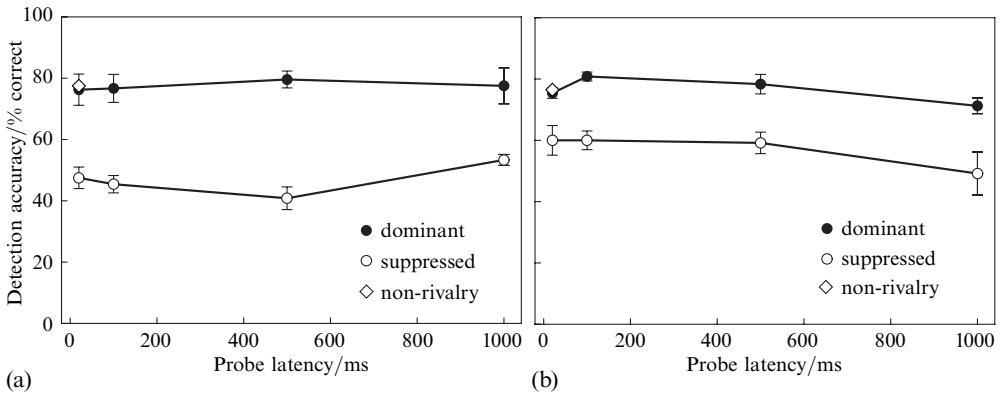
Within an experimental session, the observers were instructed to press a start key on the computer keyboard when one of the rivalrous views was exclusively dominant, either the left-eye view or the right-eye view. The observer's right-eye view always contained the CW grating (which, for motion conditions, was displayed with movement up and to the left), while the left-eye view contained the CCW grating (for motion conditions, movement down and to the left). In half of the blocks of trials, the observers initiated each trial whenever the CW grating was totally dominant, while in the other blocks they pressed the start key when the CCW grating was dominant. After the initiation of a trial, a probe spot was briefly presented for 100 ms at one of four possible temporal latencies (20, 100, 500, or 1000 ms),<sup>(1)</sup> and its appearance was synchronized with the vertical refresh of the monitor. The probe was presented either in the dominant-eye view or in the suppressed-eye view. The observer's task was to identify the location of the probe (4-alternative spatial forced choice) by pressing one of four keys. A short beep was given 1120 ms after the initiation of each trial to indicate that the trial had been completed, so that the observer could make his/her judgment. Once a trial was initiated, if there was a change in the observer's eye dominance before the presentation of the probe, the observer was instructed to abort that trial. This might occur, for example, in a session where the observer initiated trials when the CW grating was dominant. In this case, the probe should only be visible against the CW grating; if it ever became clearly visible against the CCW grating, then a change in dominance/suppression had obviously occurred before the onset of the probe. If something like this were to occur, the observer was required to abort that trial.

Within the experiment, there were a total of 32 distinct experimental conditions [4 temporal latencies of probe presentation  $\times$  2 dominance conditions (probe presented to either the dominant-eye view or the suppressed-eye view)  $\times$  2 rivalry types (stationary rivalry versus moving rivalry)  $\times$  2 dominance orientations (dominant-eye view contained either the CW or CCW grating)]. The four temporal latencies and two dominance conditions were manipulated within a single block of trials, whereas the rivalry types and dominance orientations were varied across blocks. Each observer completed 12 blocks of trials (3 blocks for each of the 4 combinations of rivalry type and dominance orientation). Within any given block of trials, 80 judgments were performed (4 temporal latencies  $\times$  2 dominance conditions  $\times$  10 repetitions). Therefore, at the end of the experiment, 960 trials had been completed by each observer (30 trials for each of the 32 experimental conditions).

<sup>(1)</sup> These latencies (1 s and shorter) were determined by the results of a preliminary pilot investigation. This pilot observation revealed that the observers' performance deteriorated markedly and many prospective trials had to be aborted at latencies longer than 1 s, because approximately 1 s after the initiation of a trial at one alternation of rivalry, another alternation of rivalry would occur before the onset of the probe. Therefore, because these latencies were too long relative to the period of the rivalry alternations, probes that were supposed to appear during the dominant phase of rivalry appeared in the subsequent suppressed phase, and vice versa. To eliminate these unwanted complications, we selected probe latencies that were 1 s or shorter, but which nevertheless spanned the entire length of one phase of rivalry alternation.

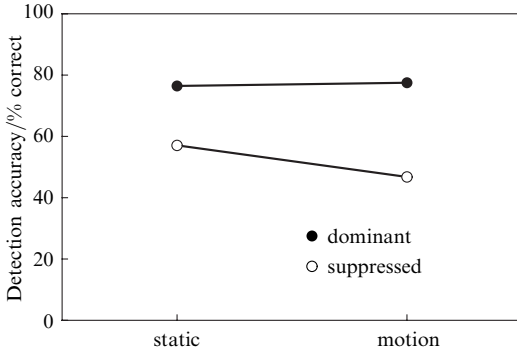
## 2.2 Results and discussion

Whether the dominant-eye view contained the CW grating or the CCW grating did not make any difference for any of the observers, in either the moving or static rivalry conditions (all  $\chi^2$ s  $< 2.8$ ,  $p > 0.05$ ). Accordingly, the results from the CW-dominant and CCW-dominant conditions were combined for each observer. Therefore, there were a total of 60 trials that were obtained for the remaining conditions for each observer. In addition, since all observers showed similar patterns of results, their data were combined and are presented in figures 2a and 2b, which show the correct detection performance for the moving and stationary rivalry conditions, respectively. One can see that, for both stationary and moving conditions, the observers' detection performance was severely impaired during the suppressed phase of rivalry as compared with that during the dominant phase, although performance was still above chance levels (25% correct). One can also see that the performance during the dominant phase of rivalry was equivalent to that measured under non-rivalry conditions. This result is consistent with the findings of previous studies (eg Blake and Camisa 1979).



**Figure 2.** The results of experiment 1 for (a) the moving rivalry and (b) the stationary rivalry conditions. The observers' detection accuracies (4-alternative spatial forced choice) are plotted as a function of probe latency. Each data point reflects the average performance of four observers. The results indicated by the open circles represent the observers' performance when the probe was presented to the suppressed eye, while the filled circles represent the observers' performance during the dominant phase of binocular rivalry. The open diamond symbol indicates the observers' performance during non-rivalry conditions. The magnitude of the difference between the two curves indicates the depth of interocular suppression caused by binocular rivalry. The error bars indicate the variability across observers, shown as  $\pm 1$  standard error.

A three-way within-subjects analysis of variance (ANOVA) was conducted on the correct detection performances, where the factors were rivalry condition (moving versus static)  $\times$  dominance condition (probe in dominant eye versus suppressed eye)  $\times$  latency (20, 100, 500, 1000 ms). The main effect of dominance condition was highly significant and accounted for 68.3% of the total variance in the observers' judgments ( $F_{1,45} = 307.615$ ,  $p < 0.001$ ). That is, the observers' detection performance was significantly reduced during the suppressed phase of binocular rivalry, relative to that obtained during the dominant phase. This finding is consistent with previous studies (eg Blake and Camisa 1979; Wales and Fox 1970). Whether the gratings were moving or static also made a significant difference, both in the main effect ( $F_{1,45} = 10.532$ ,  $p = 0.002$ ) and in the 2-way interaction between the rivalry conditions (moving versus static rivalry) and the dominance (probe in dominant eye versus suppressed eye) conditions ( $F_{1,45} = 15.797$ ,  $p < 0.001$ ). This interaction is shown in figure 3. It is readily apparent that the detection rates for both the static and motion conditions were almost identical when the probe was presented in the dominant-eye view, while they were

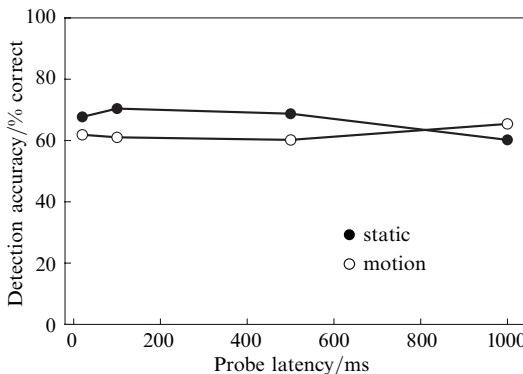


**Figure 3.** The significant interaction obtained in experiment 1 between the type of rivalry (moving versus static) and the state of the view in which the probe was presented (probe in dominant eye versus suppressed eye). The open circles represent detection performance during suppression; the filled circles represent performance during the dominant phase of binocular rivalry.

impaired more severely in the motion conditions relative to the static conditions when the probe was presented to the suppressed-eye view. These findings suggest that the magnitude of suppression is larger during motion rivalry than during static rivalry.

We manipulated the amount of time before the probe was presented in order to examine the temporal course of rivalry suppression. However, neither the main effect of latency ( $F_{3,45} = 0.725$ ,  $p > 0.05$ ) nor the interaction between latency and dominance ( $F_{3,45} = 1.175$ ,  $p > 0.05$ ) was significant. This implies that the difference between the detection performance during the dominant phase and that of the suppressed phase was essentially constant, regardless of the temporal latency. It appears that the strength of suppression remains at a constant level during a single phase of binocular rivalry. The only other statistically significant effect is that of the interaction between latency and rivalry type (moving versus static rivalry) ( $F_{3,45} = 5.557$ ,  $p = 0.002$ ). That interaction is exhibited in figure 4. When the detection performance from the dominant phase and that of the suppressed phase are combined together, there seems to be a very small decrease in probe detectability at the longest latencies for the static conditions and an equally small increase in detection performance at the longest latencies for the moving conditions. This interaction, however, only represents about 3.7% of the variance in the observers' judgments.

In summary, we found that the strength of rivalry suppression remained essentially constant during a single phase of rivalry suppression. This finding was true for both stationary and moving rivalry conditions. Our results not only confirm the findings of the previous study by Fox and Check (1972) who examined stationary rivalry, but also suggest that this constant strength of suppression throughout one phase of binocular rivalry is a general one that is not affected by particular characteristics of the rivalry stimuli themselves.



**Figure 4.** The significant interaction obtained in experiment 1 between the type of rivalry (moving versus static) and the temporal latency at which the probe was presented. The open symbols represent detection performance obtained for the moving rivalry conditions; the filled symbols represent performance for the static rivalry conditions.

### 3 Experiment 2

De Bruyn and Orban (1988) showed that human observers were very sensitive to differences in velocity (ie Weber fractions were about 7%) when the velocities of the moving stimuli fell between 4 and 64 deg s<sup>-1</sup>. The discrimination thresholds increased when the stimulus velocity was increased or decreased outside of that range. McKee (1981) also found optimal performance for speeds in the range of 2–10 deg s<sup>-1</sup>, with Weber fractions of approximately 4%–5%. In experiment 1, we chose a speed of 1.2 deg s<sup>-1</sup> because earlier research had indicated that that speed promoted the highest degree of exclusive rivalry (Blake et al 1998). However, the research of De Bruyn and Orban, and of McKee indicate that the sensitivities to speed differences of moving patterns at 1 deg s<sup>-1</sup> are lower (ie higher Weber fractions) than those for patterns that move at faster speeds of 2 deg s<sup>-1</sup> or more—for example, the speed discrimination thresholds of McKee's observers were about 4.3% for standard speeds of 2 deg s<sup>-1</sup>, and rose to 6.1% for standard speeds of 1 deg s<sup>-1</sup> (a 41% increase). The purpose of experiment 2 was to determine whether the phenomenon of constant suppression strength at all temporal latencies within a phase of binocular rivalry also occurs for faster moving rivalry stimuli, particularly at speeds for which human observers are most sensitive. To that end, we chose 2 and 4 deg s<sup>-1</sup> as the speeds for the current experiment.

#### 3.1 Method

3.1.1 *Observers.* Three out of four observers were the same as those who participated in experiment 1 (HFN, JB, and SRR). Both the new female observer (GC) and observer SRR were naïve to the purpose of the experiment. All observers had normal or corrected-to-normal vision and good stereopsis.

3.1.2 *Apparatus and stimulus displays.* In experiment 1, we presented the rivalrous gratings and the probe target on the same computer monitor, while in this experiment we used two computers to generate the rivalry gratings and the probe. The images of the gratings and the probe were optically superimposed by a beam splitter. The observers used the same Apple Power Macintosh 8500/120 that was used in experiment 1 to indicate which eye view was dominant at the beginning of each trial, etc, and to present the probe at the appropriate temporal latency. The probe was displayed on the same monitor that was used in experiment 1. The moving rivalry gratings were generated by an Apple Power Macintosh 8600/300 and were displayed on a Mitsubishi 91TXM 21-inch monitor with a resolution of 1024 × 768 pixels. The stimulus displays generated by the 8600/300 were accelerated by a Nexus GA graphics accelerator board (ATI Technologies, Inc). Since the two images from the two computer monitors were optically superimposed, the stimuli presented to the observer appeared identical to those used in experiment 1—the only difference was that the speeds of the moving gratings were faster in the current experiment. As before, the same mirror haploscope was used to present the appropriate rivalry stimuli (orthogonally oriented sinusoidal luminance gratings) to the observers' left and right eyes. All other aspects of the stimulus displays were identical to those used in experiment 1.

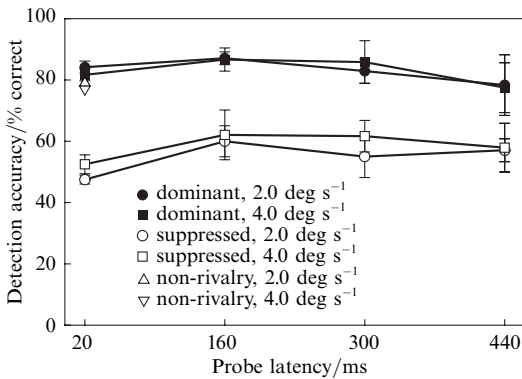
3.1.3 *Procedure.* The procedures used in this experiment were essentially identical to those used in experiment 1. The main differences between the two experiments were in terms of the speed of the moving rivalrous gratings and the latencies that were examined. The speed of the gratings in the present experiment was set at either 2 or 4 deg s<sup>-1</sup>. The results of preliminary pilot observations showed that the rate of rivalry alternation was faster with the higher motion speeds of 2 and 4 deg s<sup>-1</sup>. Accordingly, the range of latencies employed in the current experiment was reduced, so that they were all shorter than 500 ms. In particular, the probe was presented either 20, 160, 300, or 440 ms after the initiation of a trial by the observer. All other details of the procedures

were the same as those used in experiment 1. Since the results of experiment 1 showed that it did not matter whether the observers initiated a trial with either the CW or CCW grating being dominant, that variable was not manipulated in the present experiment. Two of the observers initiated trials when the CW grating was dominant, while the other two observers started trials when the CCW grating was dominant.

Within the experiment, there were a total of 16 distinct experimental conditions [4 temporal latencies of probe presentation  $\times$  2 dominance conditions (probe presented to either the dominant eye's view or the suppressed eye's view)  $\times$  2 motion speeds (2.0 versus 4.0 deg s<sup>-1</sup>)]. The four temporal latencies and two dominance conditions were manipulated within a single block of trials, whereas the speed of the moving rivalrous gratings was varied across blocks. Each observer completed 12 blocks of trials (6 blocks for each speed). Within any given block of trials, 80 judgments were performed (4 temporal latencies  $\times$  2 dominance conditions  $\times$  10 repetitions). Therefore, at the end of the experiment, 960 trials had been completed by each observer (60 trials for each of the 16 experimental conditions).

### 3.2 Results and discussion

Since all observers showed similar patterns of results, their data were combined and are shown in figure 5. In this figure, the correct detection performance is plotted as a function of latency for each of the four different combinations of dominance (ie probe in dominant eye versus suppressed eye) and speed (2.0 versus 4.0 deg s<sup>-1</sup>). A three-way within-subjects ANOVA (speed  $\times$  dominance  $\times$  latency) was conducted on the correct detection performances. The main effect of dominance was once again highly significant ( $F_{1,45} = 205.030$ ,  $p < 0.001$ ), with this factor accounting for 60.7% of the variance in the observers' judgments. The observers could detect the probe much more easily during the dominant phase of rivalry than during the suppressed phase. Once again, the performance that occurred during the dominant phase of binocular rivalry was identical to that obtained during nonrivalrous conditions.

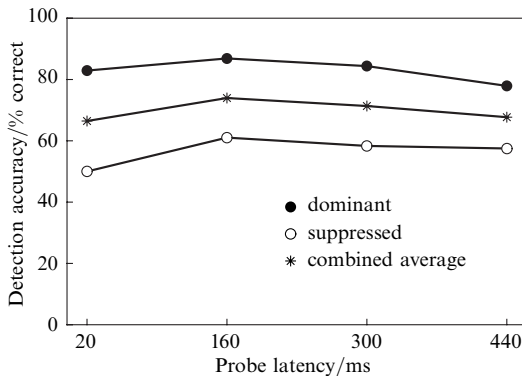


**Figure 5.** The results of experiment 2. Observers' detection accuracies (4-alternative spatial forced choice) are shown as a function of dominance (probe in dominant eye versus suppressed eye), speed of the moving rivalrous gratings (2.0 versus 4.0 deg s<sup>-1</sup>), and probe latency (ms). Each data point reflects the average performance of four observers. The results indicated by the open circles and squares represent the observers' performance when the probe was presented to the suppressed eye; the filled symbols represent the observers' performance during the dominant phase of binocular rivalry. The circles represent performance for the lower speed of motion (2.0 deg s<sup>-1</sup>); the squares represent performance for the higher speed (4.0 deg s<sup>-1</sup>). The open triangles, upright and inverted, indicate the observers' performance for the slower and faster motions, respectively, during non-rivalrous conditions. The magnitude of the difference between the curves with the filled symbols and the curves with the open circles and squares indicates the depth of interocular suppression caused by binocular rivalry. The error bars indicate the variability across observers, shown as  $\pm 1$  standard error.



In contrast, the speed of the moving rivalrous gratings did not affect performance or the strength of rivalry suppression (see figure 5). The results of the ANOVA confirmed that there were no significant effects related to the speed of the moving gratings (main effect:  $F_{1,45} = 0.876$ ; speed  $\times$  dominance:  $F_{1,45} = 1.101$ ; speed  $\times$  latency:  $F_{3,45} = 0.331$ ; speed  $\times$  dominance  $\times$  latency:  $F_{3,45} = 0.123$ ; all  $p > 0.05$ ). This finding that the speed of moving rivalrous patterns did not affect the strength of suppression is consistent with a previous phenomenon found by Blake et al (1985). In this study, faster moving dots were presented to one eye while slower moving dots (but moving in the same direction) were presented to the other eye. The velocities examined ranged from 0.375 to 12 deg s<sup>-1</sup>. Blake et al found that the difference in speed could lead to binocular rivalry, but that the faster moving dots did not necessarily predominate over the slower moving dots. Our findings are similar.

In this experiment, unlike in experiment 1, the main effect of latency was statistically significant ( $F_{3,45} = 3.480$ ,  $p = 0.023$ ), although there was no significant interaction between latency and dominance ( $F_{3,45} = 1.943$ ,  $p > 0.05$ ). One would have expected that, if there were a true change in the strength of suppression over time, the two-way interaction between latency and dominance would have been significant. This is because detection performance should not change as a function of latency when the probe is presented to the dominant eye (because there is no suppression at that point in time), but one would expect deteriorations with performance as a function of latency when the probe is presented to the suppressed eye if there were actual changes in the strength of suppression taking place. The lack of a significant two-way interaction suggests that the suppression involved in the production of binocular rivalry did not change in strength in this experiment. In any event, this significant main effect of latency was small; it accounted for only 3.1% of the variance in the observers' judgments (compare this to the 60.7% of the variance accounted for by dominance). This small main effect of latency is shown in figure 6—one can see that performance in both the dominant and suppressed phases of rivalry is slightly better for the intermediate latencies.



**Figure 6.** The results of experiment 2, collapsed across the different speeds of motion. The open symbols represent the observers' performance when the probe was presented to the suppressed eye; the filled symbols represent the observers' performance during the dominant phase of binocular rivalry. The asterisks represent the observers' performance collapsed across the dominant and suppressed phases of rivalry.

#### 4 General discussion

The aim of the present set of experiments was to examine the temporal characteristics of the binocular rivalry that occurs when human observers view contradictory patterns, both moving and static. In 1972, Fox and Check reported that the strength of rivalry suppression did not change (remained constant) throughout a single phase of binocular rivalry. Until now, this had not been examined for motion-induced rivalry, despite the fact that it has been studied on and off over the past 15 years for both human observers (eg Blake et al 1998; Wade et al 1984) and nonhuman primates (eg Logothetis and Schall 1989). The results of our experiments show that the temporal course of rivalry

suppression for motion-produced rivalry is essentially identical to the suppression that occurs for static rivalrous patterns.

This similarity in results for motion and static rivalry is especially remarkable when one considers the fact that the experience of binocular rivalry in these two cases may be due to the operation of very different cortical substrates in the brain. Neurophysiological research over the past decade, using both single-cell recordings in monkeys and fMRI techniques in humans, has shown that the visual neurons mediating binocular rivalry are located in many different cortical areas, such as V1 (Sengpiel et al 1995); V1, V2, and V4 (Leopold and Logothetis 1996); areas within the superior temporal sulcus, such as MT and MST (Logothetis and Schall 1989); inferior temporal cortex (Sheinberg and Logothetis 1997); and frontoparietal cortex (Lumer et al 1998). In particular, static-based binocular rivalry may be due to neurophysiological mechanisms within areas such as V4 (Leopold and Logothetis 1996), while motion-induced rivalry has been shown to stimulate visual neurons in MT and MST (Logothetis and Schall 1989). Our findings that the strength of suppression remains constant throughout a single phase of binocular rivalry for both moving and statically presented rivalrous stimuli show that these areas (V4, MT, MST, etc), which are often considered to lie within functionally separate pathways within the visual system (see Felleman and Van Essen 1991; Merigan and Maunsell 1993; Mishkin et al 1983), operate according to similar principles. Even if the inhibition produced by contradictory visual inputs to the two eyes occurs at a variety of levels within the visual system, it nevertheless apparently expresses itself with the same temporal characteristics.

In the past, it has been found that whenever there are moving elements within a rivalrous pattern (ie moving pattern in one eye view, static pattern in the other eye view) the moving pattern predominates, and is visible for a longer period of time during the resulting binocular rivalry (Blake et al 1998; Breese 1899). In experiment 1, we found that there is another effect of motion, that the strength of interocular suppression is greater for motion-based rivalry than for the rivalry that results from viewing discrepant static patterns (see figure 3). During the alternations of motion rivalry, the dominant-eye view suppresses the inhibited-eye view to a larger extent than is the case in conventional static rivalry. However, the results of experiment 2 showed that this larger magnitude of suppression that occurs during motion rivalry does not itself appear to be influenced by further changes in the speed of motion within a rivalrous pattern (ie faster speeds do not necessarily lead to stronger magnitudes of suppression).

In summary, we have shown that motion rivalry and static rivalry share important temporal properties—they seem to be qualitatively alike. Yet, there do seem to be some quantitative differences in the strengths of suppression and inhibition that occur. It will be the task of future research to evaluate whether there are any other substantive differences between these two types of binocular rivalry.

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