



Motion rivalry impairs motion repulsion

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Abstract

In their classic study on motion repulsion, Marshak and Sekuler (Science 205 (1979) 1399) reported a repulsion of up to 10° when two different directions of motion were presented dichoptically. However, subjects in that study did not experience binocular rivalry, presumably because of the brief presentation time. In the present study, we measured repulsion during binocular rivalry by requiring subjects to dichoptically view the stimuli until one direction of motion appeared to exclusively dominate the other (Blake, Yu, Lokey, & Norman (1998). *J. Cogn. Neurosci.*, 10, 46–60). We found that motion repulsion was significantly reduced during exclusive dominance. Indeed, after controlling for reference repulsion—the misjudgment of a single direction of motion (Rauber & Treue (1998). *Perception*, 27, 393–402)—we found no significant motion repulsion during exclusive dominance. These data suggest that motion repulsion may require the *perception*, rather than merely the physical presence, of multiple directions. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Motion repulsion; Binocular rivalry; Exclusive dominance; Reaction time

1. Introduction

Since Marshak and Sekuler (1979) first reported motion repulsion—the misjudgment of a motion direction as further away from another concurrent motion direction—many researchers have investigated the dependence of the phenomenon on various stimulus parameters (Kim & Wilson, 1996; Hiris & Blake, 1996; Rauber & Treue, 1998, 1999; Matthews, Geesaman, & Qian, 2000; Dakin & Mareschal, 2000). Most of these studies used binocular viewing conditions where both motion directions were seen by each eye, while few studies considered the dichoptic viewing condition in which the two different directions of motion were presented separately to the two eyes. However, the latter, especially repulsion during binocular rivalry, is interesting because it can help clarify the relationship between repulsion and rivalry and guide future modeling work on motion perception. In Marshak and Sekuler's initial work, a significant repulsion of up to 10° was found

during dichoptic viewing, although it was smaller than the 20° repulsion they found under the corresponding binocular viewing condition. However, they indicated that their observers did not experience binocular rivalry, presumably because of the brief (1-s) stimulus duration. In addition, a recent study showed that even when a single direction is presented, human subjects overestimate the angle (up to 9°) between that direction and the nearest cardinal axis, a phenomenon termed reference repulsion by Rauber and Treue (1998). In this paper, we controlled for reference repulsion and measured motion repulsion during binocular rivalry.

When two sufficiently different directions of motion are presented dichoptically, one direction will eventually dominate while the other is suppressed. In the current study, we asked observers to judge the dominant direction relative to that of a subsequently presented single-direction stimulus. Since reference repulsion presumably affected judgments of the dominant and single directions in the same way, the method allowed us to discount reference repulsion, and to assess the interaction between the dominant and suppressed directions during binocular rivalry. We found that the repulsion, although non-zero, was much

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smaller than that reported for the non-rivalrous case (Marshak & Sekuler, 1979). We also ran two non-rivalrous control conditions. The first control was the standard paradigm for motion repulsion—the two directions were simultaneously presented binocularly. In the second control, viewing was also binocular, but only one of the two directions was presented. Our results indicated that repulsion during binocular rivalry was more similar to the second control than to the first. Indeed, no significant repulsion was found during binocular rivalry. The data suggest that motion repulsion may require not only the physical presence, but also the perception of multiple directions.

2. Method

2.1. Observers

Two of the authors and three naive observers participated in the experiment. All had normal or corrected-to-normal vision. The experiments were undertaken with the understanding and written consent of each subject.

2.2. Apparatus and stimuli

The experiment was performed on a 21 in. ViewSonic P817 monitor controlled by a Macintosh G4 computer. The vertical refresh rate of the monitor was 120 Hz, and the spatial resolution was 1024×768 pixels. In a well-lit room, observers foveally viewed the stimuli through a mirror stereoscope. A chin rest stabilized head position at 76 cm from the monitor.

The screen had a constant veiling luminance of 27.5 cd/m^2 . The stimuli were random dot cinematograms (RDCs), seen as black dots (1.2 cd/m^2) translating within a white (115.0 cd/m^2) circular aperture that was 3° in diameter. We choose the small aperture size to avoid patchiness during rivalry. Each dot was a 2×2 pixel square (approximately 3.6 arc min on each side), that moved at a speed of $4^\circ/\text{s}$. The dot pattern for each eye was always centered at the fixation point of that eye so that the two eyes' views were aligned. The fixation point had a diameter of 10.8 arc min.

Each trial consisted of a test RDC followed by a reference RDC. Three different types of test RDCs were used: 2-motion-dichoptic, 2-motion-binocular, and 1-motion-binocular. The 2-motion-dichoptic RDCs consisted of 50 dots moving toward the upper right in one eye, and 50 dots moving toward the lower right in the other eye. Which motion direction was presented to which eye was randomized. All observers reported experiencing binocular rivalry while viewing this type of

stimulus. The remaining two types of test RDCs were non-rivalrous controls, as identical stimuli were presented to the same locations in the two eyes. In the 2-motion-binocular¹ RDCs, each eye was shown 50 dots moving in the upper-right direction simultaneously with 50 dots moving in the lower-right direction. In the 1-motion-binocular RDCs, 50 dots moved in the upper-right direction only. The upper- and lower-right directions were centered at 22.5° and -22.5° from the horizontal axis, respectively. To prevent observers from learning fixed axes-of-motion, a random angle uniformly distributed in $[-2.5, 2.5]^\circ$ was drawn in each trial; it was then added to one direction and subtracted from the other so that the mean direction of the two motions was always horizontal. Therefore, the physical directions for the upper-right motion and for the lower-right motion ranged from 20° to 25° , and from -20° to -25° , respectively.

The reference stimuli were identical to the 1-motion-binocular RDCs, except for a systematic variation in direction, which depended on the specific procedure (see below). We used these reference stimuli, instead of a subject-controlled line or marker, to access the perceived direction of the test stimuli, in order to discount reference repulsion from our results and focus on the repulsion between the two directions of motion.

Each stimulus was generated by moving a virtual aperture over a large virtual field of random dots, and then showing the dots within the aperture at a fixed region on the monitor. Due to the large number of different stimuli needed in our experiments, we computed the stimuli on-line, right before each trial. To save computational time, we generated 60 frames for each test stimulus, but presented each frame twice so that the 60 frames lasted 1 s. In the two non-rivalrous control conditions, each 1-s test RDC was presented once per trial. However, in the dichoptic condition, subjects were required to view the test RDCs until the upper-right direction exclusively dominated the lower-right direction (Blake, Yu, Lokey, & Norman, 1998), and that percept typically required stimulus durations of more than 1 s (see Section 3). Consequently, in the dichoptic condition, each test RDC 'looped' until the subject terminated the presentation. To avoid motion discontinuities that would otherwise occur every 1 s, we simply copied the first frame of the random dots in the large virtual random-dot field and pasted it to the last frame of the field.

¹ The term 'binocular' can mean either the general condition of viewing with both eyes, or the specific condition of presenting identical patterns to the two eyes. Here the latter meaning of the term is used. We prefer not to use the more specific term 'dichoptic' because of its relative obscurity.

2.3. Procedures

Two different experimental procedures were used for measuring motion repulsion: the method of constant stimuli and the staircase method. For both procedures, the three test conditions mentioned above (2-motion-dichoptic, 2-motion-binocular, and 1-motion-binocular) were run in separate blocks of trials. A trial always began with a fixation dot that remained visible for the duration of the trial. Observers initiated presentation of the first (test) RDC with a key press. In the dichoptic condition, observers waited until the upper-right direction became exclusively dominant, and then pressed a key to terminate the stimulus. The interval between the stimulus onset and the key-press was taken as the observer's reaction time. In the two non-rivalrous control conditions, the first RDC on each trial was presented for 1 s. In all three conditions, after an inter-stimulus interval of 1 s, the second (reference) RDC was shown to both eyes for 0.5 s. The observers were then required to report whether the direction of the second stimulus was clockwise (–) or counterclockwise (+) to the upper-right direction of the first stimulus. Between trials, the veiling luminance was shown for 4 s while the RDCs for the next trial were computed. Note that the dichoptic condition made it necessary to always present the test stimulus before the reference stimulus in each trial. For consistency, we applied the same order of stimulus presentation to all three conditions. Any bias that may have been introduced by this fixed order of presentation was controlled for by the results from the 1-motion-binocular condition. (In other words, the measured repulsion from the 1-motion-binocular condition would be zero if there were no presentation-order induced bias.)

It should be noted that in all three test conditions, the procedure described above measured the directional repulsion of only one motion. Assuming symmetry, the other motion direction in the 2-motion-dichoptic and 2-motion-binocular conditions must also be repulsed, resulting in a larger total overestimation of the angle between the two motion directions. For convenience, we define repulsion as the misjudged angle measured from the upper-right motion throughout this paper.

2.3.1. Method of constant stimuli

For this method, the direction of the reference stimuli varied across trials to cover a range around the upper-right direction of the test RDC. The physical differences between the reference RDC's direction and the upper-right direction of the corresponding test RDC were, randomly, 0° , $\pm 4^\circ$, $\pm 8^\circ$ or $\pm 12^\circ$. There was a block of 210 trials for each test condition, with 30 trials at each of the seven possible directional differences. All observers first completed practice blocks until they were able to distinguish the upper-right direction from the

lower-right direction in the 2-motion-binocular condition, and were familiar with the phenomenon of exclusive dominance in the dichoptic condition. During the actual experiments, the binocular conditions each required approximately 30 min to complete, including a short break every 70 trials. The dichoptic condition required 45–60 min to complete.

For each observer and test condition, we plotted the proportion of 'clockwise' responses to the seven directional differences and fit a sigmoidal function to the data. The fit was statistically significant in all cases ($P < 0.01$). Repulsion was indexed by the extent to which the midpoint of the sigmoidal function departed from zero.

2.3.2. Staircase method

In a separate experiment, we measured repulsion using two simultaneous staircases. On one staircase, the reference RDC was initially presented 10° clockwise to the test RDC. On the other staircase, the reference RDC was initially presented 10° counterclockwise to the test RDC. As before, subjects indicated whether the reference RDC was clockwise or counterclockwise to the test. Within each staircase, the angle between the two RDCs was decreased after two consecutive correct responses, and increased after two consecutive incorrect responses. The size of the increment/decrement was a random number of up to 2° . Using this procedure, the direction of the reference RDC quickly converged to the perceived direction of the test RDC. Each test condition consisted of a block of 100 trials, 50 from each staircase, randomly mixed. The directional differences from the final 25 trials on each staircase were averaged to produce a measure of repulsion.

3. Results

We now compare the results from the rivalrous, dichoptic condition with those from the two non-rivalrous controls. If the results from the dichoptic condition are similar to those from the 2-motion control condition, then motion repulsion was not affected by rivalry. On the other hand, if the results of the dichoptic condition are similar to those from the 1-motion control condition, then motion repulsion did not occur during rivalry.

3.1. Method of constant stimuli

Fig. 1 shows the responses of five observers when the method of constant stimuli was used. In each of the three conditions, the proportion of 'clockwise' responses at all seven directional differences was fitted by a sigmoidal function. For each observer, the curve in the 2-motion-binocular condition is shifted furthest to

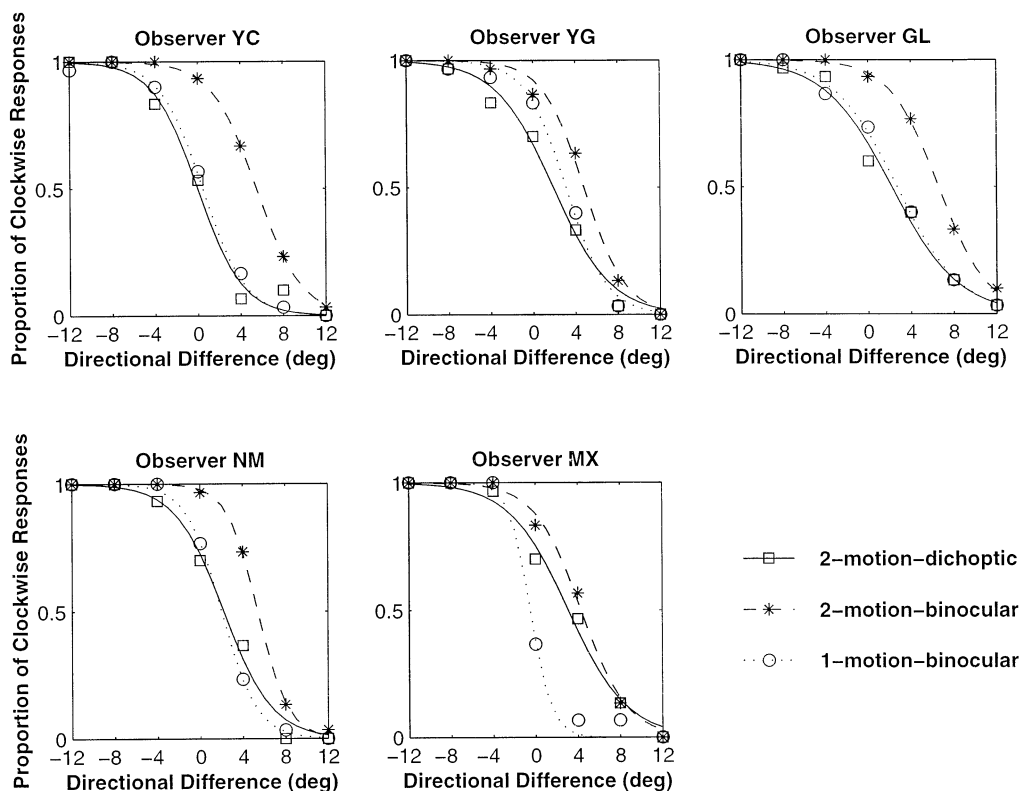


Fig. 1. Responses of five observers measured by the method of constant stimuli. Performance in the 2-motion-dichoptic, 2-motion-binocular and 1-motion-binocular conditions is shown separately for each observer. The horizontal axis represents the physical difference between the direction of the reference RDC and the upper-right direction of the test RDC. The positive and negative values indicate counterclockwise and clockwise directional changes, respectively, from the reference to the test. Each point reflects 30 trials and the seven points in each condition are fitted by a sigmoidal function. For each observer, the dashed sigmoid is shifted furthest to the right indicating that repulsion was consistently greatest in the 2-motion-binocular condition, and reduced in the dichoptic (solid) and 1-motion-binocular (dotted) conditions.

the right, indicating the largest repulsion. The positions of the curves for the remaining conditions vary among observers. For all but one observer (MX), the curves for the 2-motion-dichoptic and 1-motion-binocular conditions are closer to each other than to the 2-motion-binocular condition. This suggests that repulsion during binocular rivalry is greatly reduced. (A possible explanation of MX's outlier behavior is provided in the Section 4.)

In Fig. 2, the magnitude of the repulsion, which corresponds to the angular difference at the mid-points of the functions in Fig. 1, is shown separately for each condition. Interestingly, the mean repulsion in our 2-motion-binocular condition was only 5.3° , considerably less than the 20° repulsion reported in the earlier study (Marshak & Sekuler, 1979). This difference may be owing to the removal of reference repulsion (Raubert & Treue, 1998) from the present data, due to the use of the reference stimuli (see Section 2). In fact, Raubert and Treue (1999) found that, after controlling for reference repulsion, motion repulsion was reduced from 22° to 7° . This is in good agreement with our result of 5.3° . Importantly, the mean repulsion values for the 2-motion-dichoptic condition and the 1-motion-binocular

conditions were only 1.9° and 1.6° , respectively, and a within-subjects ANOVA revealed that there was no significant difference between the two conditions ($F(1, 4) = 0.15$, $P = 0.72$). This suggests that motion repulsion is diminished when one direction perceptually dominates the other during binocular rivalry. Additionally, the failure to find significant motion repulsion in our 2-motion-dichoptic condition cannot be easily explained by a lack of statistical power. This is because the same level of statistical power was sufficient to demonstrate that repulsion in the 2-motion-binocular condition significantly exceeded repulsion in the 1-motion-binocular condition ($F(1, 4) = 39.82$, $P = 0.003$), and the 2-motion-dichoptic condition ($F(1, 4) = 22.35$, $P = 0.009$). The mean repulsion for the 1-motion-binocular condition was 1.6° instead of 0° , probably because a bias was introduced by the fixed presentation order of the test and reference stimuli (see Section 2). This bias should be the same for all three conditions, and therefore should not affect our conclusions.

In the 2-motion-dichoptic condition, observers were instructed to view the stimuli until they experienced exclusive dominance. To assess whether the observers viewed the stimuli for durations sufficiently long to

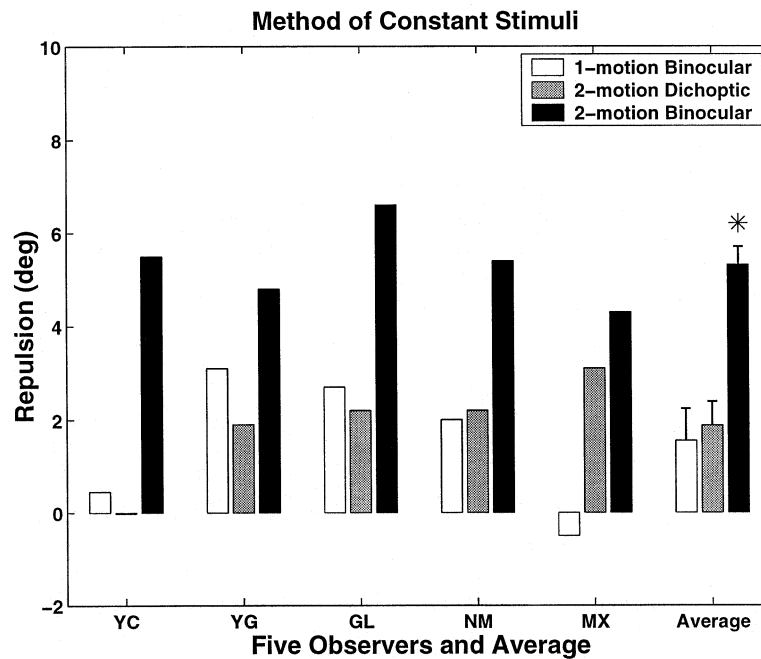


Fig. 2. Motion repulsion for all five observers in the three test conditions, corresponding to the angular difference at the midpoints of the sigmoidal curves in Fig. 1. The average across observers is shown in the right most columns, where the error bars represent one standard error. The mean repulsion values were 1.6°, 1.9° and 5.3° in the 1-motion-binocular, 2-motion-dichoptic, 2-motion-binocular conditions, respectively. Overall, repulsion was significantly greater in the 2-motion-binocular condition than in either of the other two conditions, which did not differ significantly from each other.

permit binocular rivalry, we recorded reaction time in the 2-motion-dichoptic condition. The data are plotted in Fig. 3. We found that, for most subjects, the reaction-time distribution appeared to have a fast component and a slow component, with each component being well fit by a Gamma probability distribution. The solid curves in Fig. 3 represent the fitting results with the sum of two weighted Gamma distributions. It is likely that the fast component corresponds to those trials on which the judged direction (i.e. the upper-right direction) was initially dominant, while the slow component corresponds to those trials on which the judged direction was initially suppressed, and the subjects had to wait for it to become dominant. The slow component is wider than the fast component presumably because when the upper-right direction was initially dominant, subjects quickly terminated the stimuli without waiting through the entire duration of the dominance, while when the lower-right direction was initially dominant, subjects had to wait through the duration of the dominance. Although purely objective measures of exclusive dominance may be impossible, the 2-component characteristic of our reaction-time distributions is consistent with what would be expected if the initial dominance/suppression alternated between the two directions across trials. Note that previous studies usually measured the distribution of the *dominance duration* (Levelt, 1965; Fox & Herrmann, 1967) instead of the

distribution of reaction time to the *dominance onset* of a given stimulus shown in Fig. 3.

Another interesting feature in Fig. 3 is that each observer showed a *minimum* reaction time x_0 , whose average value across observers was 1.11 s. In addition, the mean and median reaction times across the subjects were 3.42 and 2.64 s, respectively. Since the simple motor response (i.e. pressing of a single, fixed key) would likely contribute less than 200 ms to the reaction times (Welford & Brebner, 1980), the formation of binocular rivalry must require a minimum of about 1 s, and typically much longer. This may explain why Marshak and Sekuler (1979) reported that their observers did not experience binocular rivalry. In their dichoptic condition, stimuli were shown for only 1 s, a duration that may not have been sufficient to permit reliable binocular rivalry. In fact, in our experiment, subjects responded in less than 1 s on just 1.5% of the trials.

3.2. Staircase method

The data obtained from our staircase procedure are shown in Fig. 4. There are some quantitative differences between the amount of repulsion obtained using the staircase method and the method of constant stimuli. For example, in the 2-motion-dichoptic case, observer NM shows greater repulsion in the staircase procedure (Fig. 4) than in the method of constant

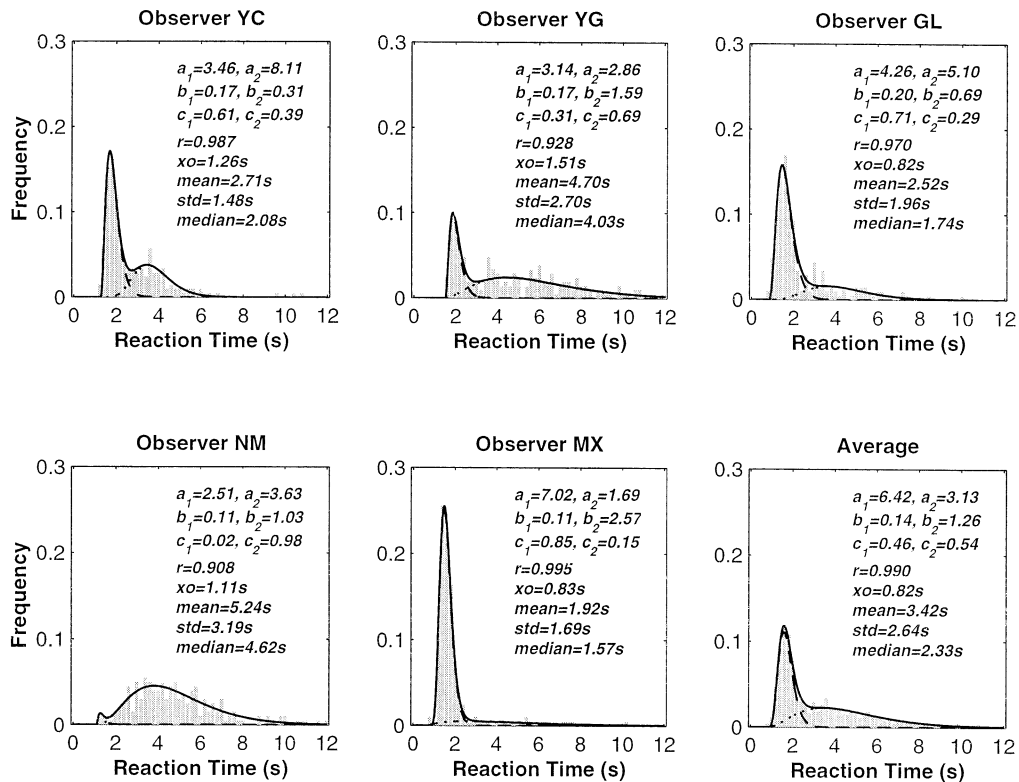


Fig. 3. Distribution of reaction times for all five observers in the 2-motion-dichoptic condition using the method of constant stimuli. The average across observers is shown in the lower right panel. The solid lines show the fit with a summation of two weighted Gamma distributions $f(x) = c_1\gamma(x - x_0, a_1, b_1) + c_2\gamma(x - x_0, a_2, b_2)$, where $\gamma(x, a, b) = (1/\Gamma(a)b^a)x^{a-1}e^{-x/b}$ and $\Gamma(a)$ is the standard Gamma function that normalizes the Gamma distribution. The x_0 parameter was set to the shortest reaction time for each subject, and was not a variable of the curve fitting. The dashed and dotted lines show the two weighted Gamma distributions, respectively. r is the correlation coefficient that measures the goodness of fit. The mean, standard deviation, and median of each distribution are also listed. Note that the parameters for the 'average' panel are not necessarily equal to the average of the parameters across the individual observers. For example, x_0 of the 'average' panel, by definition, should be equal to the smallest x_0 among the individual subjects.

stimuli (Fig. 2). However, the overall pattern in Fig. 4 is similar to that in Fig. 2. Specifically, in both figures, each observer shows the greatest repulsion in the 2-motion-binocular condition. Also, as was true for the method of constant stimuli, the staircase method revealed statistically greater repulsion in the 2-motion-binocular condition than in either the 2-motion-dichoptic ($F(1, 4) = 22.86$, $P = 0.009$) or 1-motion-binocular ($F(1, 4) = 24.18$, $P = 0.008$) conditions. Additionally, as before, repulsion in the 2-motion-dichoptic condition was statistically indistinguishable from that in the 1-motion-binocular condition ($F(1, 4) = 0.94$, $P = 0.39$). These data therefore again suggest that motion repulsion was diminished when one of the directions was suppressed by the other during rivalry.

4. Discussion

In this paper, we studied motion repulsion during binocular rivalry and two non-rivalrous controls. One

control was the standard paradigm for motion repulsion, and the other was a single motion case. We found that binocular rivalry significantly attenuated motion repulsion, and this was true whether the method of constant stimuli or a staircase method was used. A further comparison showed that repulsion during rivalry was statistically indistinguishable from repulsion in the single motion case. This suggests that the suppressed direction did not affect how subjects perceived the dominant direction during binocular rivalry. Taken together, the present results imply that motion repulsion requires the *perception*, and not merely the physical presence, of multiple directions.

Another interesting finding is that in the dichoptic condition, it usually took a minimum of about 1 s for subjects to indicate exclusive dominance, and that the distribution of the reaction times had a fast and slow component. As we mentioned above, the fast component may correspond to trials on which the judged direction (i.e. the upper-right direction) was initially dominant, while the slow component may correspond to the trials on which the judged direction was initially

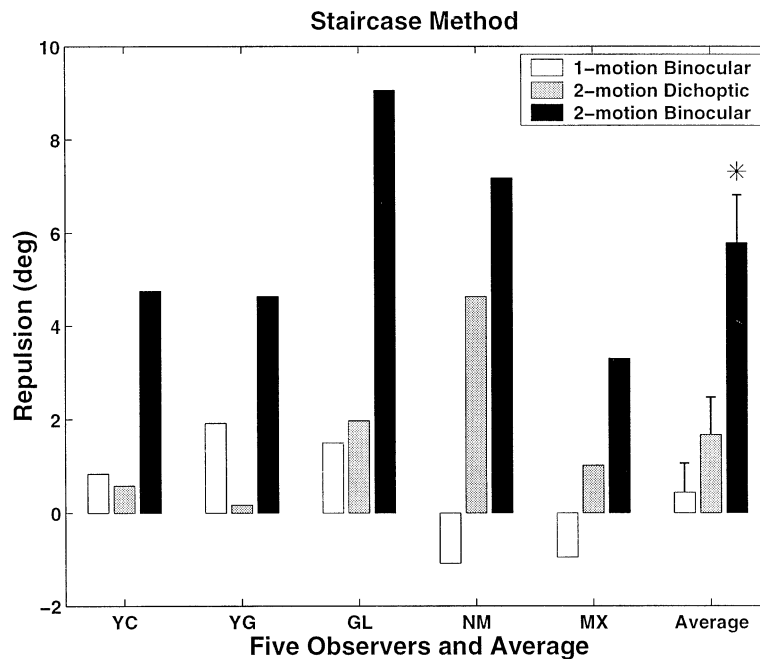


Fig. 4. Motion repulsion with the staircase method for the same three conditions and five observers as in Fig. 2. The average values across all five observers are shown in the right most columns, which were 0.4°, 1.7° and 5.8° in the 1-motion-binocular, 2-motion-dichoptic, and 2-motion-binocular conditions, respectively. As in Fig. 2, repulsion was significantly greater in the 2-motion-binocular condition than in either of the other two conditions, which did not differ significantly from each other.

suppressed, and the subjects had to wait for it to become dominant. Subject NM is the only observer who showed a predominantly slow component in the reaction time distribution (Fig. 3). Indeed, he reported after the experiment that he tended to see the lower-right direction as dominant at the beginning of most trials. In contrast, subject MX's distribution was heavily biased towards the fast component, but when asked, she reported that she had not mainly seen the upper-right direction as initially dominant. It is therefore likely that she simply did not wait long enough to reach exclusive dominance on many of the trials. This could partially explain why her results under the dichoptic condition were different from those of the other subjects in Figs. 1 and 2, and more similar to the dichoptic results of Marshak and Sekuler (1979) whose subjects did not experience rivalry. The fact that different subjects showed different weightings between the fast and slow components in Fig. 3 cannot be explained by the difference in eye balance among the subjects because each eye was presented with the two motion directions equally often. Rather, it could be a reflection of the different sensitivities or attentional states to the two motion directions, and different criteria for dominance.

In our experiment, the rivalrous 2-motion-dichoptic condition differed from the other conditions with respect to stimulus duration. Specifically, since the subjects had to wait for the occurrence of exclusive dominance, the presentation time of the test stimuli in the 2-motion-dichoptic condition was usually longer

than that in the other conditions. The mean time was 3.42 s with the method of constant stimuli, and 4.59 s with staircase method. By contrast, only a 1-s movie was shown for the 2-motion-binocular and 1-motion-binocular control conditions. Additionally, observers were required to terminate the presentation of the test stimuli in the 2-motion-dichoptic condition, but not in the control conditions. These differences might have affected repulsion. To rule out this possibility, we conducted an auxiliary experiment, in which five observers (two of the authors and three new naive observers) freely controlled the duration of the test stimuli in the 2-motion-binocular condition. To prevent the observer from responding too quickly, the stimuli were presented for 3 s before the observers were able to terminate them. In separate blocks of trials, the same observers also judged the same stimuli with the standard 1-s presentation time as before. The results are shown in Fig. 5. The repulsion values in degrees (measured as the directional differences at the midpoints of the sigmoidal curves) for the two durations were (5.5, 4.9) for YC, (1.7, -0.1) for AT, (3.3, 4.6) for BW, (6.2, 5.2) for NM, and (-0.1, 1.4) for XW.² There was no consistent nor significant difference between the short and long presentation times ($F(1, 4) = 0.06$ and $P = 0.81$, n.s.).

² Observers AT and XW were different from other observers in that they showed little repulsion under both conditions, presumably because their reference repulsion was strong enough to account for nearly all of the directional misjudgment.

It is possible that an attentional difference between the 2-motion-binocular and 2-motion-dichoptic conditions could have contributed to the difference in the observed repulsion. Specifically, the subjects' attention might have been focused on the dominant motion in the 2-motion-dichoptic condition, resulting in a diminished repulsion, while their attention might have been divided between the two motions in the 2-motion-binocular condition, leading to a significant repulsion. This difference could occur despite the fact that the subjects were instructed to judge the upper-right motion in both conditions. It would be interesting to examine this possibility in the future by integrating an attentional manipulation into repulsion experiments.

Our finding, that the suppressed stimulus did not influence the perceived direction of the dominant stimulus, is reminiscent of previous work relating binocular rivalry to visual detection. For example, it has long been known that during dominance, detection thresholds for stationary stimuli are equivalent to those during ordinary viewing (Fox & Check, 1968; Collyer & Bevan, 1970; Wales & Fox, 1970). More recent work has shown that motion stimuli, too, are readily detected during dominance (Blake et al., 1998). Therefore, the detection studies, like the present investigation of per-

ceived direction, suggest that the dominant stimulus is largely unaffected by the suppressed stimulus.

While the suppressed stimulus may not affect the perceived direction of the dominant stimulus, there is evidence that the suppressed stimulus can nevertheless influence the state of the motion system. In particular, it has been demonstrated that suppressed motion stimuli generate motion aftereffects (MAEs) (Lehmkule & Fox, 1975; Blake, 1995). The fact that suppressed stimuli generate MAEs without generating motion repulsion implies that the neural events mediating MAEs are at least partially independent from those which determine perceived direction. Such a dissociation would also be consistent with Levinson and Sekuler's (1976) earlier psychophysical finding that MAEs do not contribute to adaptation-induced shifts in perceived direction. Furthermore, the dissociation would be consistent with the fact that motion repulsion is independent of binocular disparity between the two directions of motion (Hiris & Blake, 1996) while MAEs are disparity specific (Regan & Beverley, 1973; Anstis & Hassis, 1974).

Recent human imaging studies have shown significant correlations between MAEs and activity in area MT/V5 (Tootell et al., 1995; He, Cohen, & Hu, 1998;

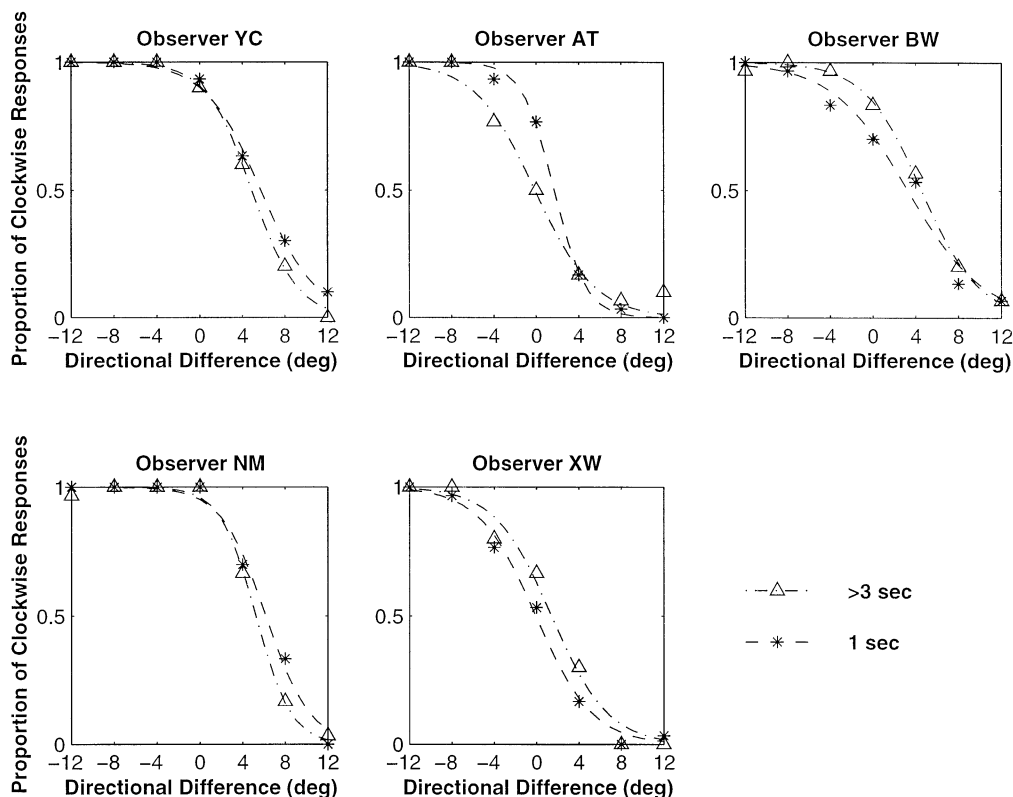


Fig. 5. Responses of five observers to the 2-motion-binocular stimuli measured by the method of constant stimuli. The dashed-curves through stars are from the standard 1-s presentation condition, as was used for the dashed curves in Fig. 1. The dot-dashed curves through triangles are from the condition where the observers were required to terminate the test stimuli after 3 s of presentation. There was no significant difference in repulsion between the two conditions.

Hautzel et al., 2001). Similarly, single cell recordings in the macaque monkey have revealed that MT neurons (Snowden, Treue, Erickson, & Andersen, 1991; Qian & Andersen, 1994) demonstrate strong inhibition between different directions of motion, and such inhibitory interactions may be responsible for MAEs. The disparity-specificity of MAEs (Regan & Beverley, 1973; Anstis & Hassis, 1974) can be explained by the disparity-dependence of the directional inhibition in MT (Qian, Andersen, & Andersen, 1994; Bradley, Qian, & Andersen, 1995). In contrast, the directional inhibition in MT is unlikely to be responsible for motion repulsion because the inhibition is reduced by disparity between different motion directions (Bradley et al.) while motion repulsion is not affected by disparity (Hiris & Blake, 1996). We therefore speculate that area MT may play an important role in MAEs but not in motion repulsion. The fact that during binocular rivalry, the suppressed stimuli generate MAEs (Lehmkule & Fox, 1975; Blake, 1995) without generating motion repulsion (present study) further suggests that motion repulsion and rivalry might involve neuronal events different from those responsible for MAEs. Future models of motion processing that seek to explain the relationships among MAEs, motion rivalry, and motion repulsion may have to take these considerations into account.

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