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Effect of Attention on the Initiation of Binocular Rivalry

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Abstract
Recent studies suggest that attention is necessary for perceptual alternations in binocular rivalry. It has been shown that attention plays a role in not only accelerating but also even enabling perceptual fluctuation in ongoing phase of binocular rivalry. In this study, we tested whether attention also plays a role in suppressing a rival stimulus in its initial phases by measuring proportions of mixed dominance. We hypothesized that when attention is directed toward the location of rival stimuli prior to their presentation, the proportion of mixed dominance is lower than when attention is directed away from that location because of attentional facilitation. However, we found that the proportion of mixed dominance did not differ depending on the locus of attention, although we adopted well-established experimental paradigms for manipulating spatial attention. This result suggests that attention is not a determining factor in establishing initial perceptual dominance in binocular rivalry.

Keywords
Attention, binocular rivalry, initiation, mixed dominance

Introduction

When our eyes encounter two incompatible images, our perception alternates between the two images overtime. This intriguing phenomenon, which is called binocular rivalry, has received much interest because it dramatically portrays that our perceptual experience can be dissociated from the physical state of the stimuli.

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One of the defining characteristics of binocular rivalry is that rivalry suppression does not occur at the time when the stimuli are presented but starts about 150 millisecond after the onset of the stimuli. Wolfe (1983) showed that when rival images are flashed briefly, we tend to perceive a fused image of the rival stimuli, which he called "abnormal fusion." That is, it takes a certain amount of time for either of the competing images to achieve dominance over the other. Carter and Cavanagh (2007) termed this period "onset rivalry" and argued that there is a fundamental difference between this initial fused state and subsequent alternation phases of binocular rivalry. They found that initial dominance was not determined probabilistically but rather strongly biased toward one percept over the other. This bias differed across spatial locations within each individual, and across individuals. Because the idiosyncratic nature of the onset rivalry is maintained over multiple weeks, the authors suggested that it is related to low-level visual processing, and insensitive to top-down influences by our cognitive system.

The view that onset rivalry is unaffected by top-down factors led us to question whether this state of rivalry is influenced by attention. Contrary to the characteristics of onset rivalry, researchers have long hypothesized that binocular rivalry is tightly coupled with attention (Wheatstone, 1838; von Helmholtz, 1925). It has been shown that attention affects binocular rivalry dynamics, such as prolonging the perceptual dominance of an attended stimulus (Chong, Tadin, & Blake, 2005; Lack, 1978; Meng & Tong, 2004), and increasing the alternation rate (Paffen, Alais, & Verstraten, 2006). Attention also biases which item is perceptually dominant in the initial phases of binocular rivalry (Chong & Blake, 2006; Hancock & Andrews, 2007; Mitchell, Stoner, & Reynolds, 2004). Attention can also influence rivalry dynamics by facilitating local adaptation. Adaptation is a key factor in perceptual alternations of binocular rivalry. Adaptation to one of the competing stimuli makes the adapted stimulus weaker; consequently, the other tends to achieve perceptual dominance (Blake, Sobel, & Gilroy, 2003; Kang & Blake, 2010). Attention can promote this local adaptation preferentially for the dominant item (Chong & Blake, 2006; Jung & Chong, 2014).

For instance, Jung and Chong (2014) showed that when attention is directed to the competing stimuli under binocular rivalry, attentional boost in adaptation is found from the dominant item, but not from the suppressed items. However, as these studies mainly focused on the ongoing perceptual fluctuations of binocular rivalry, it is not yet clear whether attention also influences rivalry dynamics in the initial phase.

To fill this gap in existing knowledge, we investigated whether attention influences perceptual dynamics of onset rivalry. With perspectives derived from Carter and Cavanagh (2007), we assumed that onset rivalry is a distinctive period, whose characteristics might be different from those in later states of binocular rivalry. If attention operates in a similar way during onset rivalry, it should disambiguate the rivalry faster, thereby decreasing the period of onset rivalry—attention is known to increase the degree of perceptual adaptation (Chaudhuri, 1990; Lankheet & Verstraten, 1995). However, if the state of onset rivalry is independent of top-down influences (Attarha & Moore, 2015; Carter & Cavanagh, 2007), its duration would not be influenced by attention.

To manipulate attention, we adopted a modified version of the attentive tracking task (Cavanagh, 1992), which allowed us to manipulate spatial attention without overt shifts of eye movements. For this task, participants were asked to track two out of four objects and the color of each object was continuously changing. In each trial, there was a target color: Participants were asked to report whether the target color appeared on either of the two attended objects, while ignoring the other two objects. Because all four objects rotated along an imaginary circle surrounding the fixation point and the two targets were always on opposite sides of the fixation point, the best tracking strategy was to maintain fixation at the center. We then presented two orthogonally oriented gratings in one of four locations, to measure the effect of attention on the initiation of rivalry. This tracking method enabled us to maintain the same speed of attention shift between the tracked (i.e., attended) and ignored (i.e., unattended) objects because the distance of the attentional shift from the fixation point to the rivalry site was always the same, regardless of attentional loci. We asked participants to track two target objects instead of one for them to have the equivalent amount of attentional shift between in the attended and unattended conditions. If we had asked participants to track only one item, in the unattended condition, they would have moved their attention from the single attended location to the unattended location to report their percept during the onset rivalry while they would not have needed to shift their attention in the attended condition.

Consequently, this additional time to shift attention from attended to unattended location would always lead to slower resolution of perceptual ambiguity in the unattended condition than in the attended condition. Because there were the dual, equidistanced targets from the central fixation, participants would need an attentional shift from the dual targets to the single rival location in both the attended and unattended conditions.

In Experiment 1, participants were instructed to track stimuli rotating along an imaginary circle and to detect a target color. In this task, participants' attention was directed to or away from the location where rival stimuli were to be presented. In Experiment 2, we used a rapid serial visual presentation (RSVP) task to generalize our results and to tightly control the locus of attention. In this experiment, participants' attention was directed away from the rival stimuli presented in the periphery when detecting target letters among centrally presented letter sequences. To probe how quickly attention resolves perceptual ambiguity, in both experiments, we measured the proportion of mixed dominance for the two rival stimuli, while varying the duration of the rival stimulus presentation.

Experiment 1

We manipulated participants' spatial attention with a tracking task. Figure 1 shows the stimulus sequence, which consisted of three phases: cueing, tracking, and rivalry. In the

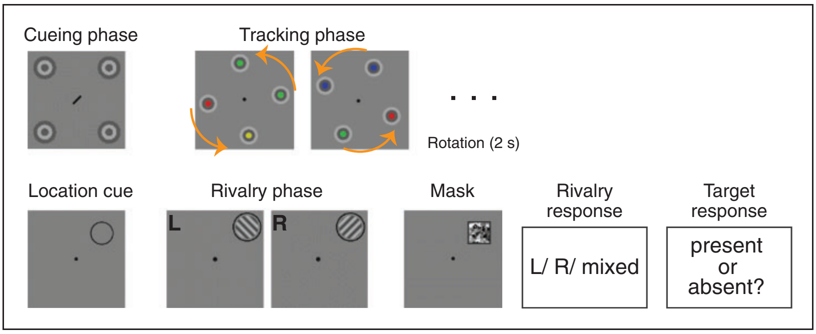

Figure 1. Illustration of the experimental procedure in Experiments 1A and 1B. After a line indicated the two target objects, all four objects rotated for 2 second. Subsequently, a location cue appeared briefly to indicate where the gratings would be presented. For rivalry trials, the orientations of the two gratings were perpendicular to each other, while they were the same in catch trials. A Mondrian patch was presented as a mask after the gratings were presented to control the duration of stimuli precisely. Participants reported whether the perceived orientation of the grating was tilted to the left, to the right, or mixed, and then also responded whether the target color was presented in either of the two target objects.

cueing phase, participants were instructed to attend to two locations facing each other, which were indicated by a line cue. The tracking phase followed the cueing phase, wherein the four circles rotated counterclockwise for 2 second, completing a single cycle, while the filled color of each circle changed every 250 millisecond. Participants were asked to detect the target color at those two cued circles, while ignoring color changes within the other two uncued circles. In the rivalry phase, a ring-shaped location cue was briefly presented in one of the four locations occupied by the four circles and the rival stimuli were presented at that location with variable durations, resulting in two conditions. In the attended condition, the rival stimuli were presented in one of the two attended locations (i.e., tracked locations), whereas in the unattended condition, the rival stimuli were presented in one of the two unattended locations. Participants were then asked to report their percepts (i.e., left-tilted grating, right-tilted grating, or a mixed-dominance percept). If attention facilitates resolving perceptual dominance, the proportion of mixed dominance would be higher for the unattended condition than for the attended condition, while overall mixed dominance would decrease with increasing stimulus duration (Mitchell et al., 2004; Wolfe, 1983).

Method

Apparatus

All stimuli were created using the Psychophysics Toolbox of MATLAB (Brainard, 1997; Pelli, 1997). Stimuli were presented via two Samsung 22″ CRT monitors (85 Hz refresh rate, 49.53 cd/m^2 maximum luminance, and 0.031° in dot pitch), whose luminance profile was linearized, and a conventional mirror stereoscope was used for dichoptic stimulation. Participants' heads was fixed via a chin-and-forehead rest at a distance of 60 cm from the monitors.

Participants

Twenty-eight observers, including two of the authors, participated in Experiment 1 (16 women, 12 men; aged 19–42 years) after they signed an informed consent form approved by the Institutional review board of Yonsei University. All reported normal color vision and visual acuity. Twelve participants completed Experiment 1 A, and 16 completed Experiment 1B. Three participants' data from Experiment 1 A and six participants' data from Experiment 1B were excluded from analyses because their rivalry dynamic was slower than our longest stimuli duration or they experienced the mixed percept for a majority of the stimuli duration. Specifically, for Experiment 1 A, one participant was excluded because the proportion of mixed-dominance responses was over 99% for the entire condition. The other two participants were excluded because the proportion of their mixed-dominance responses increased with the stimuli presentation time, which suggests they might have had difficulties in experiencing binocular rivalry. For Experiment 1B, two participants' data were excluded from analysis because the proportion of mixed-dominance responses was more than 87% and the data from the other four participants were not included because the entire mixed-dominance response was less than 13%. However, including those data sets did not change the pattern of the results associated with key findings. All except the authors received a monetary reward for their participation and were naïve to the purpose of the study.

Stimuli

The stimuli of the tracking phase consisted of four circles, which were presented in the upper right, upper left, lower right, and lower left locations from the central fixation point, respectively. Each tracking circle consisted of three concentric rings whose diameters were 0.63°, 1.25°, and 1.88° of visual angle. The distance from the fixation point to the center of the circles was 2.5°. The color of the outer and inner rings was dark gray (35 cd/m^2), whereas the middle ring was light gray (64 cd/m^2). The colors of the inner circles were randomly chosen from a set consisting of red, yellow, green, blue, and purple. In the rivalry phase, two sinusoidal gratings with different orientations (45° and 135°) were used. The diameter, contrast, and spatial frequency of each grating were set to 1.25°, 30%, and 3 c/deg, respectively. We also used a ring-shaped location cue, whose width was 0.08° and diameter was 2°, and Mondrian-patterned square masks (2° in width) in the rivalry phase.

Procedure

The procedure is shown in Figure 1. The four tracked items were presented together with a tilted line (either left-diagonal or right-diagonal direction) indicating the two items to be attended in the cueing phase. The tracking phase started when the participant depressed the spacebar. All four items rotated counterclockwise for 2 second, while the inner color of each tracking object changed every 250 millisecond. Participants had to detect a target color that was presented within the attended items in 50% of trials. In the other 50%, the target color did not appear within the attended items but did appear in the unattended items. The target color was shown before the first trial and changed after every 20 trials. After the 2 second of the tracking phase, all tracking items disappeared, and a location cue was presented for 200 millisecond, indicating where the rival stimuli would appear. In the attended condition, rival gratings were presented in one of the two attended locations that had been tracked during the tracking phase. In the unattended condition, the gratings were presented in one of the two unattended locations. The rival stimuli were presented for 50, 150, 300, 450, 750, or 1050 millisecond, and a Mondrian patch followed as a mask. To insure that participants were correctly reporting their perceptual dominance, we occasionally (33% of trials) presented the same stimuli dioptically (catch trials). We also replicated the experiment with the same design (Experiment 1B) but different stimulus durations—50, 150, 200, 250, 300, or 350 millisecond— so as to examine the dynamics at the early stage of binocular rivalry, while other aspects of the experiment were identical to the first experiment. Participants reported their perceived orientation via three forced-alternative choices (left-tilted grating, right-tilted grating, or mixed) and then reported whether the target color was present during the tracking phase. Auditory feedback was given for only the incorrect color detection task. Participants completed a total of 384 rivalry trials and 192 catch trials over 2 days, during which the attended and unattended conditions were given with equal probability.

In analyzing the data, we adopted a Bayesian approach in addition to traditional null hypothesis significance testing. We calculated the Bayes factor for all the analyses of variance (ANOVAs) and *t* tests performed in this study with the BayesFactor package for R (Rouder, Morey, Speckman, & Province, 2012; Rouder, Speckman, Sun, Morey, & Iverson, 2009). The Bayes factor refers to the probability of the data under one hypothesis relative to that under another one. Here, we tested the alternative hypothesis supporting our experiment manipulation versus the null hypothesis. Therefore, if the Bayes Factor is over 1, it supports the alternative hypothesis, and if it is less than 1, it supports the null hypothesis. When it is over 3, it is considered moderate evidence favoring the alternative hypothesis (Lee & Wagenmakers, 2013).

Results

Before analyzing the data for binocular rivalry, we examined performance for detecting the target color in order to ensure participants were actually engaged in the task. The average performance was 87.67% for Experiment 1A ($SD = 7.18$) and 87.88% for Experiment 1B ($SD = 7.662$), suggesting that participants did attend to the target objects during the tracking phase.

Figure 2 shows the proportion of mixed dominance as a function of stimulus duration. We first analyzed the results of the catch trials in Experiments 1A and 1B. Participants correctly reported the orientation except when the stimulus duration was 50 millisecond, for which the mixed-dominance response was 64.58% in Experiment 1A and 60% in Experiment 1B (Figure 2(c) and (d)). Confirming that our catch trials were effective as a control, there was neither main effect of attention (Experiment 1A, $F(1, 8) = 0.1366$, $p = .713$, JZS $BF_{10} = .207$; Experiment 1B, $F(1, 9) = .007$, $p = .935$, JZS $BF_{10} = .194$) nor an interaction between the effect of attention and stimulus duration (Experiment 1A, $F(5, 40) = .0637$, $p = .997$, JZS $BF_{10} = .0067$; Experiment 1B, $F(5, 45) = .0185$, $p = .999$, JZS $BF_{10} = .058$).

In the subsequent analyses, we tested whether attention influenced the initiation of rivalry. With increasing stimulus duration, the proportion of mixed dominance decreased similarly for both the attended (Figure 2(a), black line) and unattended conditions (Figure 2(a), gray line), indicating that participants' perception was quickly established into one of the two rival stimuli, but the influence of attention was limited. A two-way ANOVA with factors of stimulus duration and attention (attended vs. unattended) confirmed these observations. There was a significant main effect of stimulus duration, $F(5, 40) = 24.483$, $p < .001$,

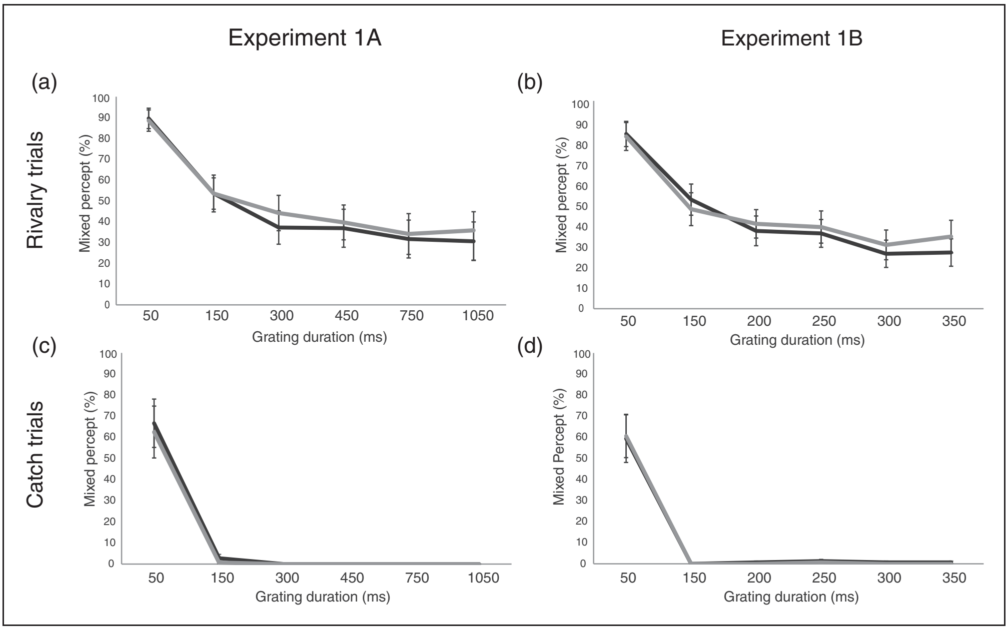

Figure 2. The proportion of mixed-percept responses for rivalry trials in (a) Experiment 1A and (b) Experiment 1B, and of catch trials in (c) Experiment 1A and (d) Experiment 1B. Black lines indicate the attended condition, and gray lines indicate the unattended condition. Error bars indicate the standard error of the mean.

JZS $BF_{10} = 2.749 \times 1E7$. However, the effect of attention was not significant, $F(1, 8) = 2.258$, $p = .171$, JZS $BF_{10} = .223$, and it did not interact with the stimulus duration, $F(5, 40) = 1.445$, $p = .229$, JZS $BF_{10} = .069$. Both the effect of attention and interaction between attention and the stimulus duration seem to have moderate evidence for null hypothesis when evaluated with Bayesian analyses (Lee & Wagenmakers, 2013).

We replicated the experiment with short stimulus durations because the attended condition seemed to show smaller proportions of mixed dominance, especially at the 300-millisecond stimulus duration in Experiment 1A. We concerned that the insufficient resolution of the stimulus duration of Experiment 1A could have resulted in insignificant main effect of attention, and thus, we used a finer stimulus durations in Experiment 1B. The result of this replication (Figure 2(b)) was that attention did significantly hasten the initial dominance of binocular rivalry. A two-way ANOVA with factors of stimulus duration and attention revealed a significant effect of stimulus duration, $F(5, 45) = 26.503$, $p < .001$, JZS $BF_{10} = 6.882 \times 1E9$.

Importantly, attention did not influence the initial dominance, $F(1, 9) = 2.413$, $p = .155$, JZS $BF_{10} = .209$; but there was a significant interaction between attention and stimulus duration, $F(5, 45) = 3.666$, $p = .007$, JZS $BF_{10} = .0.066$, such that the proportion of mixed dominance was larger in the unattended condition than the attended condition, especially at longer stimulus durations. However, this effect was not convincing when evaluated with Bayesian analysis. Furthermore, it is injudicious to conclude that the proportion of mixed dominance significantly differed between the attended and unattended conditions based on the interaction between stimulus duration and attention because pairwise *t* tests revealed no differences between the two conditions at any stimulus duration (*p*s > .066). Bayes factors for *t* tests also show an anecdotal effect of attention; for 50 millisecond: JZS $BF_{10} = .365$, for 150 millisecond: JZS $BF_{10} = 1.422$, for 200 millisecond: JZS $BF_{10} = 1.196$, for 250 millisecond: JZS $BF_{10} = .683$, for 300 millisecond: JZS $BF_{10} = .8$, for 350 millisecond: JZS $BF_{10} = 1.491$. Given the weak and inconsistent results of Experiments 1A and 1B, we decided to test our hypothesis again in Experiment 2.

Experiment 2

In Experiment 1, we did not find consistent evidence that attention facilitates the initiation of binocular rivalry. However, the task used in Experiment 1 might have not been sufficient in diverting attention as the attended and unattended objects were presented in the same imaginary circle trajectory. Furthermore, to indicate the location of rival stimuli, we used a circular cue, which would have diluted the effect of attention toward the target in the tracking task because the cue could have operated as an exogenous cue for both the attended and unattended conditions. To address these concerns, we modified the task in Experiment 2.

First, we eliminated the location cue presented prior to the onset of rival stimuli, based on the concern that the abrupt onset of that location cue in Experiment 1 might have exogenously drawn attention to the location where the rival stimuli were presented, thus weakening our manipulation of spatial attention. Second, we manipulated spatial attention similarly to a previous study that established the role of attention in rivalry alternations (Brascamp & Blake, 2012). Specifically, we prepared two different tracking tasks for the attended and unattended conditions. In the attended condition, spatial attention was deployed to the location of rival stimuli by requiring participants to track target colors similar to Experiment 1. In the unattended condition, attention was directed away from the location of rival stimuli by requiring participants to count target letters rapidly presented in the center of the display (Figure 3). If attention facilitates resolving perceptual ambiguity in the initial phases of binocular rivalry, the proportion of mixed dominance should be smaller in the attended condition than in the unattended condition.

Method

Apparatus & Stimuli

All aspects of the apparatus and stimuli for the color detection task and binocular rivalry were the same as those used in Experiment 1. For the RSVP task designed to direct attention to the fixation point, we used red or blue letters whose size was approximately $0.2^\circ \times 0.3^\circ$.

Participants

Nine observers (5 women; aged 22–26 years) participated in Experiment 2 after they signed informed consent forms approved by the institutional review board of Yonsei University. They had normal color perception and acuity, received a monetary reward, and were naïve to the purpose of the study. Three participants' data were excluded from the analyses because the proportion of the mixed dominance was too small to reveal any sizeable effect (below 16.6% across all trials). However, including those data did not change the pattern of the results.

Procedure

Participants performed two different tasks in the attended and unattended conditions during the tracking phase (Figure 3). In the attended condition, they performed a color detection task that was similar to the tracking task of Experiment 1, such that participants were asked to track color changes of the two cued circles, and the rivalry stimuli were always presented in one of the tracked locations. For the unattended condition, participants were instructed to

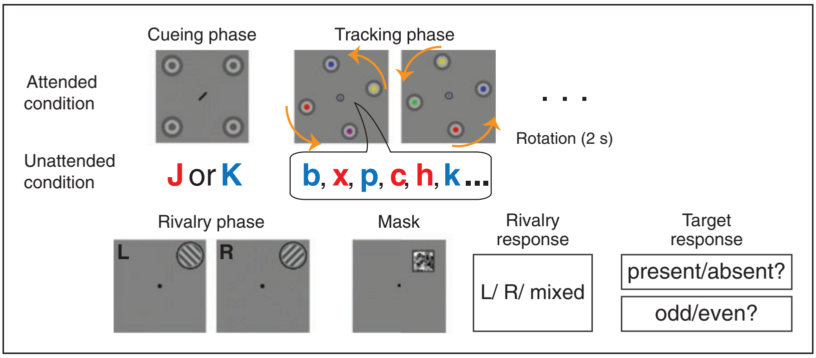

Figure 3. Experimental procedure in Experiment 2. In the attended condition, participants tracked the two target objects and detected whether a target color was presented within either of the target objects, as in Experiment 1. In the unattended condition, participants counted how many times the target letters (red J and blue K) were presented within a rapid serial stream of letters in the center of the display. Unlike Experiment 1, there was no location cue, in order to avoid any possible attentional shift. Gratings and the mask were presented as in Experiment 1. Participants reported the perceived orientation of the rivalry gratings. After that, They also reported either the presence of the target color (in the attended condition) or whether an odd or even number of target letters appeared (in the attended condition).

attend to the center of the screen and asked to perform a letter-counting task. In the letter-counting task, participants counted how many times target letters were presented, and reported whether the number of target was odd or even. The target letters were a blue "j" and a red "k." Distractors were blue and red letters "b," "c," "e," "h," "p," "x," and "t" with a blue "k" and a red "j." Before the experiment, the speed of the letter presentation was adjusted for each participant, using a 1 up/1 down staircase procedure, which ended after six reversals. The average presentation time for a letter was 342 millisecond, and the standard deviation was 48 millisecond. The letter-counting task lasted for 2 second. Importantly, the stimulus configuration was always the same between the attended and unattended conditions. The only difference between the two conditions was the task. The rivalry phase was identical to that of Experiment 1, except that we removed the brief location cue that followed the tracking phase. The duration of the rival stimuli was set to 20, 80, 150, 300, 450, or 750 millisecond. The same mask as in Experiment 1 immediately followed. Participants completed a total of 288 rivalry trials and 144 catch trials for both the attended and unattended conditions. The attended and unattended conditions were tested in different blocks (two blocks for each condition). Participants performed a block per day, and it took 4 days for each participant to finish the experiment. Task order was randomized for each participant, with the constraint that two blocks of each condition had to be completed before they moved on to the other condition. Participants showed similar performance for both tasks in each condition (color-tracking task [the attended condition]: accuracy = 87.56%, $SD = 6.323$; RSVP task [the unattended condition]: accuracy = 81.89, $SD = 14.36$). There was no difference in performance across the tasks, $t(5) = 1.236$, $p = .271$.

Results

Figure 4 shows the result of Experiment 2. Similar to Experiment 1, the proportion of mixed dominance decreased with increasing stimulus duration for both the attended and unattended conditions. As in Experiment 1A, we found no significant difference in the proportion of mixed dominance between the attended (black line) and unattended (grey line) conditions (Figure 4(a)). A two-way ANOVA with factors of stimulus duration and attention (attended vs. unattended) yielded a significant main effect of stimulus duration ($F(5, 25) = 26.962$, $p < .001$, JZS $BF_{10} = 9.243 \times 1E10$), but no effects of attention ($F(1, 5) = .566$, $p = .486$, JZS $BF_{10} = .261$), nor an interaction between the two factors ($F(5, 25) = 1.206$, $p = .335$, JZS $BF_{10} = .108$).

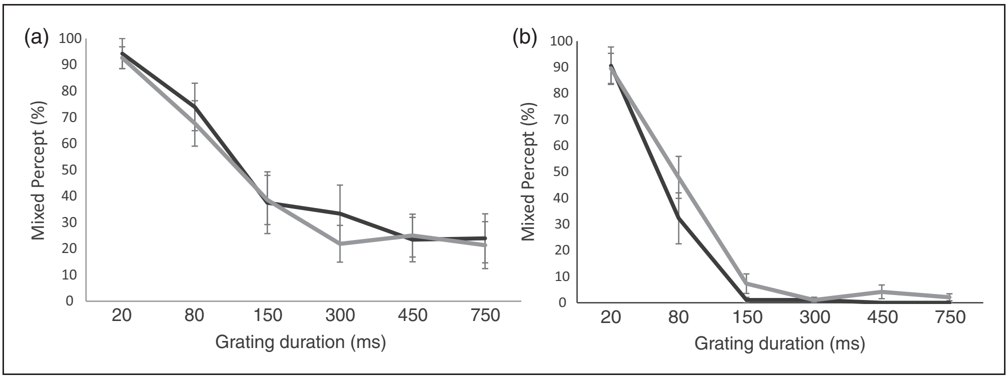

Figure 4. The proportion of mixed-percept responses in Experiment 2 for (a) rivalry trials and (b) catch trials. Other aspects of the figure are the same as in Figure 2.

The catch trials again served their purpose, in that participants reported the correct orientation with rare errors for stimulus durations longer than 150 millisecond (Figure 4(b)). The mixed-dominance responses were slightly more frequent in the unattended condition than in the attended condition, but differences were not statistically different (for the effect of attention, $F(1, 5) = 4.53$, $p = .073$, JZS $BF_{10} = .306$; for the effect of stimulus duration, $F(5, 25) = 110.22$, $p < .001$, JZS $BF_{10} = 2.35 \times 1E26$; for the interaction, $F(5, 25) = 1.18$, $p = .328$, JZS $BF_{10} = 0.117$).

Discussion

In the present study, we investigated whether attention hastens the initiation of binocular rivalry. We measured the proportion of mixed-dominance perceptions for briefly presented rival stimuli, while varying stimulus duration, in order to measure the influence of attention overtime. Over the two experiments, we consistently found that the proportion of mixed dominance decreased with increasing stimulus duration, but the decrease did not depend on the locus of attention prior to the presentation of rival stimuli. These findings suggest that although attention is a critical factor for perceptual alternations in binocular rivalry (Chong et al., 2005; Lack, 1978), it does not determine how quickly one of the competing items achieves perceptual dominance over the other.

Our findings may seem at odds with compelling evidence that attention is closely related to diverse aspects of binocular rivalry, including its initial perceptual dominance (Dieter & Tadin, 2011; Ling & Blake, 2012; Ooi & He, 1999; Paffen et al., 2006). However, it should be noted that those previous studies did not examine how quickly attention facilitates resolving perceptual ambiguity during binocular rivalry. Rather, they primarily focused on whether attending to competing items enables the attended item to achieve initial dominance over the unattended item (Chong & Blake, 2006; Hancock & Andrews, 2007; Mitchell et al., 2004). A comparison of the current and previous studies suggests that although attention can bias which of the competing items achieves dominance, it cannot shorten the time taken to resolve the competition in the initial stages of binocular rivalry.

Similarly, Dieter, Melnick, and Tadin (2015) showed that there is temporal specificity concerning when attention can modulate the dynamics of binocular rivalry. They found an influence of exogenous attention on binocular rivalry when it was present for more than a third of the average dominance duration, such that there was time for attention to have a modulatory effect. We assume that their results can also explain the characteristics of onset rivalry (Carter & Cavanagh, 2007). Similar to early-stage dominance duration in ongoing rivalry, there exists limited accumulated conflict during onset rivalry, such that attention can have modulatory effect. Therefore, it is less likely that rivalry dynamics are influenced by attention when the rivalry items are presented briefly, as shown in the present study. Further studies on temporal aspects of attentional influence in binocular rivalry are necessary to reveal how these two mechanisms interact.

One may suspect that attentional modulation by the task (either color-tracking or RSVP task) might have not carried over to binocular rivalry phase, which could dilute the attentional influence on rivalry items. We argue against this concern for the following reasons. First, we adopted the paradigm that was shown to be effective for testing attentional effect on ongoing perceptual alternations of binocular rivalry in which a rivalry phase followed the RSVP task (Brascamp & Blake, 2012). Therefore, attentional modulation in our study should be effective for the items presented even after the task. Second, accuracy for both the color tracking performance in Experiment 1 and letter counting performance in Experiment 2 was high enough (81%–87%) to show that our participants were sufficiently engaged in the task. It is possible that in both the attended and unattended conditions, the onset of rivalry items can attract exogenous attention. Nevertheless, it is not likely that exogenous attention cancels out the attentional boost from the tracking task as the effect of endogenous attention has been found in a study using a similar paradigm (Brascamp & Blake, 2012).

Casanova, Campos, Sanchez, and Super (2013) reported that the onset time of binocular rivalry was longer for individuals with Attention Deficit Hyperactivity Disorder (ADHD) compared with controls. Consequently, they suggested that attention can mediate the duration of mixed percepts in binocular rivalry by shortening the period of each individual mixed percept. However, since the aspects of attention that shows deficits in ADHD patients are still unknown, it is possible that their findings were based on levels of inhibition or general arousal rather than endogenous attention (Hooks, Milich, & Lorch, 1994; Shaw & Brown, 1999). Our findings support this possibility, as the manipulation of spatial attention did not hasten the initiation of binocular rivalry.

Our results provide useful constraints for models of binocular rivalry dynamics. Several models have suggested reciprocal inhibition as a mechanism underlying binocular rivalry, such that the pools of neurons representing rival stimuli inhibit each other (Brascamp et al., 2007; Kang & Blake, 2010; Moreno-Bote, Rinzel, & Rubin, 2007). Attention can be easily integrated into these models as excitatory inputs serving facilitation of rivalry suppression (Dieter & Tadin, 2011; Ling & Blake, 2012; Tong, Meng, & Blake, 2006). However, these models do not posit a difference between the initial state of binocular rivalry and the ongoing perceptual fluctuations. According to recent studies, the early phases of binocular rivalry may be fundamentally different from the ongoing fluctuation phase (Carter & Cavanagh, 2007, Stanley, Forte, Cavanagh, & Carter, 2011) and less likely to be affected by top-down influences. For example, Attarha and Moore (2015) showed that for complex motion stimuli or semantic information, expectations generated from one's perceptual history cannot bias the initial dominance in binocular rivalry.

Consistent with this study, we observed that attention did not modulate mixed dominance for briefly presented rival stimuli. Thus, attention is necessary for maintaining the temporal dynamics of rivalry (Brascamp & Blake, 2012; Zhang, Jamison, Engle, He, & He, 2011) and determines which of the competing items to achieve the initial dominance (Chong & Blake, 2006; Mitchell et al., 2004), but it cannot initiate rivalry faster.

Declaration of Conflicting Interests

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