Perception, 2007, volume 36, pages 288 – 298

DOI:10.1068/p5494

The role of voluntary and involuntary attention in selecting perceptual dominance during binocular rivalry

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Received 27 July 2005, in revised form 22 May 2006; published online 7 February 2007

Abstract. When incompatible images are presented to corresponding regions of each eye, perception alternates between the two monocular views (binocular rivalry). In this study, we have investigated how involuntary (exogenous) and voluntary (endogenous) attention can influence the perceptual dominance of one rival image or the other during contour rivalry. Subjects viewed two orthogonal grating stimuli that were presented to both eyes. Involuntary attention was directed to one of the grating stimuli with a brief change in orientation. After a short period, the cued grating was removed from the image in one eye and the uncued grating was removed from the image in the other eye, generating binocular rivalry. Subjects usually reported dominance of the cued grating during the rivalry period. We found that the influence of the cue declined with the interval between its onset and the onset of binocular rivalry in a manner consistent with the effect of involuntary attention. Finally, we demonstrated that voluntary attention to a grating stimulus could also influence the ongoing changes in perceptual dominance that accompany longer periods of binocular rivalry. Voluntary attention did not increase the mean dominance period of the attended grating, but rather decreased the mean dominance period of the non-attended grating. This pattern is analogous to increasing the perceived contrast of the attended grating. These results suggest that the competition during binocular rivalry might be an example of a more general attentional mechanism within the visual system.

1 Introduction

Binocular rivalry occurs when incompatible images are presented simultaneously to corresponding regions of the two eyes. While either image on its own would be seen clearly, simultaneous presentation causes one image to be suppressed from awareness. Although this phenomenon is of importance in understanding both binocular vision and the mechanisms of visual awareness, the neural mechanisms of dominance and suppression during rivalry are not established (Andrews 2001; Blake and Logothetis 2002; Alais and Blake 2005). Traditionally, the debate about the mechanism underlying rivalry has centred on whether suppression is eye-based or stimulus-based. The former supposes inhibitory interactions at an early stage in visual processing, prior to binocular confluence, such as in V1 or the lateral geniculate nucleus (Blake 1989; Lehky and Blake 1991; Tong and Engel 2001). On the other hand, stimulus-based models propose that competition is between high-level form representations in binocular neurons (Logothetis et al 1996; Andrews and Purves 1997), possibly sharing a common mechanism with other multistable phenomena. More recently, eye- and stimulus-based accounts have been integrated into a multi-level model in which rivalry is the result of distributed neural events throughout the visual system (Blake and Logothetis 2002; Wilson 2003).

Visual attention also involves competition between objects with one stimulus among a variety of alternatives being selected for enhanced perceptual processing. This has led to the suggestion that binocular rivalry and attention might be related processes (Helmholtz 1867/1962; Leopold and Logothetis 1999). Support for this line of reasoning comes from neuroimaging studies that reveal frontal and parietal regions of the brain

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are selectively active during the switches in perception that accompany rivalry (Lumer et al 1998; Lumer and Rees 1999) and other ambiguous stimuli (Kleinschmidt et al 1998); these brain regions are often associated with selective attention and motor planning (Corbetta et al 1993; Nobre et al 1997). Consistent with these findings, a number of reports have shown that lesions to frontal and parietal regions affect the switches in perception that occur when viewing binocular rivalry and other ambiguous stimuli (Ricci and Blundo 1990; Meenan and Miller 1994; Bisiach et al 1999; Bonneh et al 2004). The behavioural evidence for high-level executive processes controlling perceptual dominance during binocular rivalry is less clear. Some studies have shown that it is possible to select and sustain a dominant stimulus with attention (Lack 1978; Ooi and He 1999; Mitchell et al 2004; Chong et al 2005). However, other reports suggest that attention has only a minimal effect (Hering 1879/1942; Blake 1988; Meng and Tong 2004), and that any effect of attention could be explained by eye movements or retinal adaptation.

The aim of this study is to explore how involuntary and voluntary attention influences the perceptual dominance of a stimulus during binocular rivalry between oriented contours. Involuntary attention is a relatively fast process that has a transient, facilitatory influence on perception (Posner and Cohen 1984; Nakayama and Mackeben 1989). In this study, we used a cuing paradigm (Posner and Cohen 1984; Mitchell et al 2004) to ask how involuntary attention could influence the initial selection of a stimulus during contour rivalry. Voluntary attention, on the other hand, has a slower, but more sustained influence on perception (Posner and Cohen 1984). We have also asked whether a task requiring voluntary attention influences the dominance of a stimulus during prolonged periods of contour rivalry.

2 Methods

Stimuli were programmed with a VSG2/5 graphics card (CRS, Rochester, England) and were presented on a Clinton Monoray monochrome monitor (mean luminance: 9.3 cd m^{-2}) with a frame rate of 120 Hz. Gamma correction was used to ensure that the monitor was linear over the entire luminance range used in the experiments. Subjects viewed the display in a darkened room at a distance of 2.28 m through Ferro-Electric Shutter Goggles (CRS, Rochester, England) that alternately occluded the two eyes at the same frequency as the frame rate of the monitor. The display also alternated on successive frames so that each frame was seen by only one eye with no perceptible flicker. In all three experiments, subjects fixated on a dark spot that remained visible throughout the experiments. Responses were recorded via a CB3 response box (CRS, Rochester, England). Stimuli consisted of sine-wave gratings (size: 1 deg of visual angle; spatial frequency: 4 cycles deg^{-1}) presented centrally on a neutral background. The gratings were oriented at 45° (right-tilted) or 135° (left-tilted). All eleven subjects had normal or corrected-to-normal vision: subjects 1–4 took part in all three experiments, subjects 5–7 took part in experiment 2, and subjects 8–11 took part in experiment 3. Seven of the subjects were naive to the purposes of the experiment.

2.1 *Experiment 1*

The aim of this experiment was to determine whether involuntary attention can influence the selection of one rival image over the other during binocular rivalry. The experimental design is shown in figure 1. On each trial, subjects viewed a fixation spot prior to the presentation of two orthogonal oblique patches of grating (contrast, 0.5) to both eyes for 787 ms (96 frames). One of the gratings was rotated in both eyes by 8° clockwise or counterclockwise. The cued grating returned to its original orientation after 164 ms (20 frames) and after a further 164 ms, one grating was removed from the image in each eye to produce rivalry. This gave a stimulus onset asynchrony (SOA) of 328 ms.

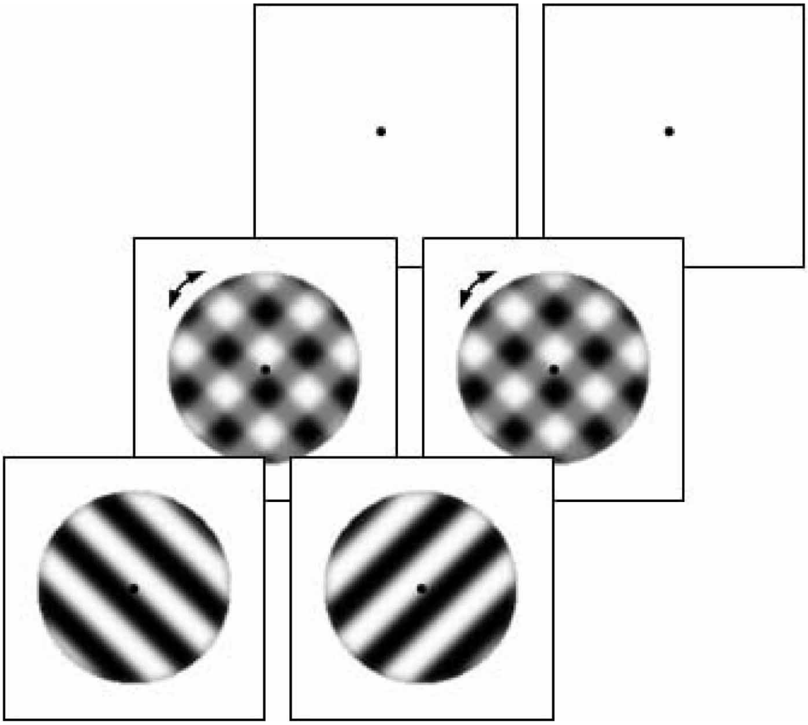

Figure 1. Schematic diagram showing the paradigm used in experiments 1 and 2. Subjects fixated a central dark spot while viewing a plaid stimulus that was presented to both eyes. One of the component gratings making up the plaid rotated clockwise or counterclockwise (arrows) before returning to its original orientation. After a delay, the cued grating was removed from the image in one eye and the uncued grating was removed from image in the other eye, generating binocular rivalry. Subjects were required to indicate the cued grating, the direction of cue rotation, and the dominant percept at the end of the rivalry period.

The duration of the rivalry period varied between 164 and 1836 ms (20 – 448 frames). At all times throughout each trial the fixation spot remained visible. At the end of the trial, subjects reported the dominant percept during binocular rivalry (left-tilted grating, right-tilted grating, or piecemeal). With the longest rivalry durations, it is possible that perceptual alternations could occur within the trial. Subjects were required to report which grating was cued and the direction of the perturbation. The purpose of this response was to check that the subjects perceived the cue. All combinations of eye of presentation (which eye received which grating), grating cued, direction of cue (clockwise or counterclockwise), and rivalry duration were presented (40 trial combinations). Each of these trials was presented twice in a block in a randomised order and each subject completed 5 blocks.

2.2 *Experiment 2*

Next, we determined the temporal characteristics of involuntary attention on binocular rivalry judgments. The procedure was the same as in experiment 1 (figure 1) except that we varied the interval between the onset of the cue and the onset of rivalry (SOA). The duration of the rivalry period was fixed at 590 ms (72 frames), because a strong cueing advantage was found for all subjects in experiment 1. The SOA varied between 328 and 2000 ms. Each interval was presented in a block of 32 trials. Each subject performed between 5 and 7 blocks for each interval in a random order.

2.3 *Experiment 3*

Finally, we determined how voluntary attention could influence predominance during longer periods of binocular rivalry. Subjects viewed orthogonal gratings (of the same spatial frequency and size as in experiments 1 and 2). Stimuli were presented independently to the two eyes during 20 trials. The gratings had the same spatial frequency, but different contrast (0.5, 0.4). During the rivalry period, the orientation of the high-contrast grating was changed briefly by 3° in a clockwise or counterclockwise direction (see experiment 1). The number of orientation changes ranged from 0 to 2 and the changes occurred at random times during each trial. The task was to fixate on a continuously visible central spot, indicate changes in perception (left-tilted grating, right-tilted grating, and piecemeal) and, at the end of each trial, report the number of orientation changes. We compared rivalry judgments during two conditions: passive and attended. Prior to presentation of the grating stimuli a letter (L or R) was presented binocularly in the centre of the screen. In the passive condition, no instructions were given regarding the letter. In the attended condition, subjects were informed that if the letter L preceded a trial, changes in orientation would only occur in the left-tilted grating, and vice versa if the letter R preceded a trial. The cue letter always identified the grating that would receive the orientation changes; this was also the higher-contrast stimulus. The orientation and eye of the attended stimulus and the frequency of orientation change and the eye were selected randomly on each trial. 50 trials were performed for each viewing condition. The passive viewing condition was always presented before the attended condition to prevent subjects becoming aware of the significance of the cue letters in the passive condition.

3 Results

3.1 *Experiment 1*

We found that when involuntary attention was directed toward a grating stimulus it was perceived to be dominant more often than an uncued grating during binocular rivalry (figure 2). The cued grating was reported dominant at the end of each rivalry period on about 60% of trials (mean $\pm$ SEM $= 59\% \pm 3.5\%$), whereas the uncued grating was only reported dominant on about 20% of trials (mean $\pm$ SEM $= 19\% \pm 1.8\%$). Piecemeal rivalry was reported on the remaining 20% of trials (mean $\pm$ SEM $= 21\% \pm 4.1\%$). Repeated-measures ANOVA revealed a significant effect of rivalry duration on cued grating reports ($F_{4,12} = 3.59$, $p < 0.05$). No significant effects of rivalry duration were evident on the uncued ($F_{4,12} = 1.60$, $p = 0.24$) or piecemeal ($F_{4,12} = 2.38$, $p = 0.11$) reports. In addition to the rivalry task, subjects were also asked to report on which grating was cued and the direction of orientation change. This task was performed accurately by all subjects (mean $\pm$ SEM $= 97.43\% \pm 0.9\%$).

We calculated the difference in the percentage of cued and uncued reports (cue effect). Repeated-measures ANOVA was performed to show that the cue effect varied significantly with the duration of rivalry ($F_{4,12} = 4.41$, $p < 0.05$), with a maximum effect occuring between 500 and 900 ms (590 ms: mean $\pm$ SEM $= 47.6\% \pm 4.9\%$; 885 ms: mean $\pm$ SEM $= 45.6\% \pm 6.4\%$). Importantly, there was a significant effect of the cue at all rivalry durations (164 ms: $t_3 = 4.33$, $p < 0.05$; 295 ms: $t_3 = 8.93$, $p < 0.01$; 590 ms: $t_3 = 9.65$, $p < 0.01$; 885 ms: $t_3 = 7.14$, $p < 0.01$; 1836 ms: $t_3 = 7.24$, $p < 0.01$). This indicates that the effect of attention had developed within 164 ms of the cue and was sustained for at least 1836 ms. We also performed an ANOVA to examine the effect of rivalry duration on the difference between the percentage of cued and piecemeal rivalry reports ($F_{4,12} = 2.95$, $p = 0.07$).

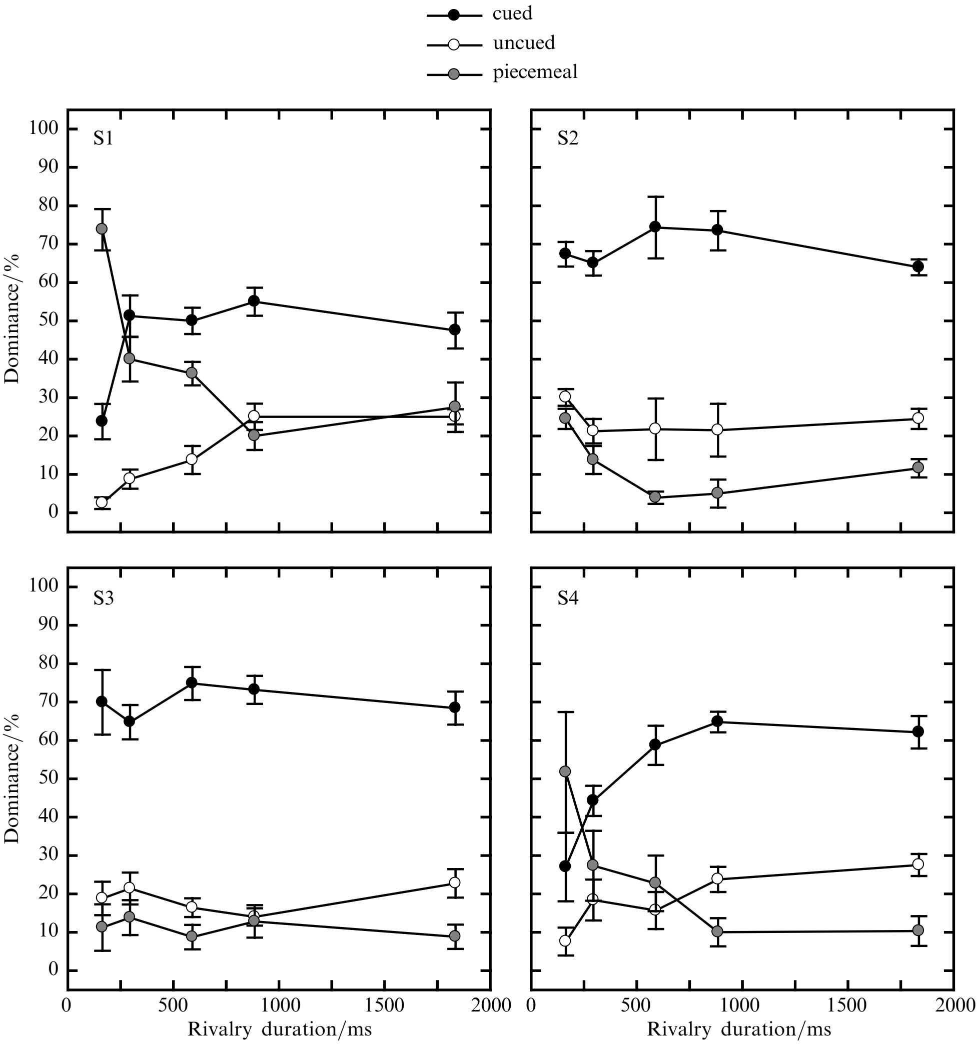

Figure 2. Data of individual subjects (S1 – S4) from experiment 1. Mean percentage of trials in which the cued grating, the uncued grating, or piecemeal rivalry was reported as a function of the rivalry period. Error bars represent ± 1 SEM.

3.2 *Experiment 2*

The influence of involuntary attention on judgments of rivalry was dependent on the interval between the onset of the cue and the onset of rivalry (figure 3). Repeated-measures ANOVAs with SOA as a within-subjects factor were performed on the data. Figure 3a shows there was a significant effect of SOA on cued ($F_{4,24} = 4.52$, $p < 0.01$) and uncued ($F_{4,24} = 4.43$, $p < 0.01$) reports. However, there was no effect on piecemeal rivalry ($F_{4,24} = 1.88$, $p = 0.15$). Figure 3b shows the cue effect for different SOAs. There was a significant effect of SOA on cue effect across all subjects ($F_{4,24} = 5.09$, $p < 0.01$). The cued stimulus was reported more often than the uncued stimulus for SOAs below 460 ms (328 ms: mean $\pm$ SEM $= 30.5\% \pm 8.9\%$, $t_6 = 3.43$, $p < 0.05$; 459 ms: mean $\pm$ SEM $= 25.9\% \pm 9.4\%$, $t_6 = 2.76$, $p < 0.05$). However, for SOAs above 750 ms, the effect of the cue declined and subjects failed to report a significant bias toward the cued stimulus (754 ms: mean $\pm$ SEM $= 12.5\% \pm 12.2\%$, $t_6 = 1.02$, $p = 0.35$; 1049 ms: mean $\pm$ SEM $= 3.7\% \pm 7.7\%$, $t_6 = 0.48$, $p = 0.65$). Two subjects

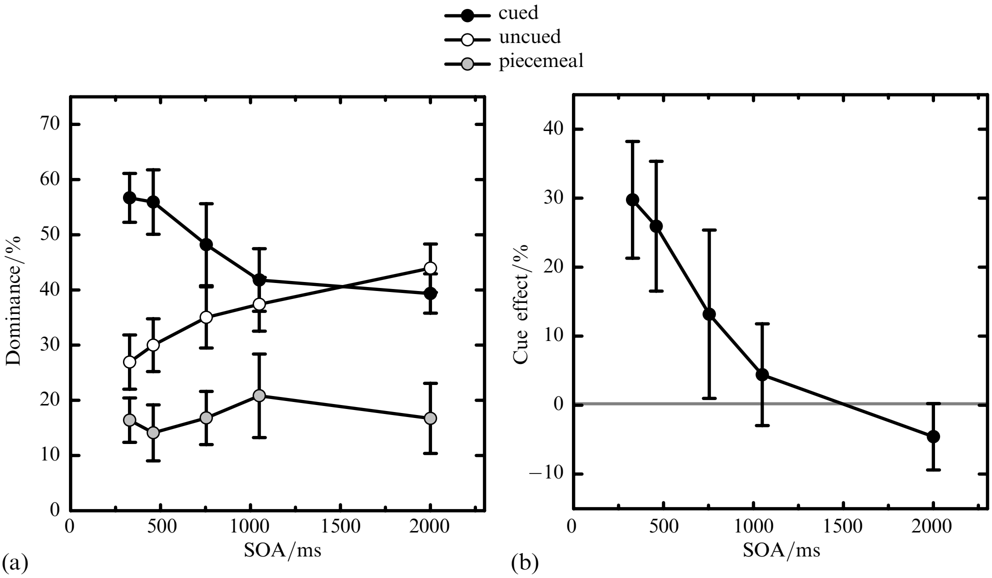

Figure 3. Group data from experiment 2. (a) Mean percentage of trials in which the cued grating, the uncued grating, or piecemeal rivalry was reported as a function of the SOA. (b) Mean cue effect across all subjects as a function of SOA. The cue effect is the difference in the percentage of trials where the cued grating was reported to be dominant compared to the uncued grating. The SOA is the delay between the onset of the cue and the onset of binocular rivalry. Error bars represent ±1 SEM.

even demonstrated a bias towards the uncued stimulus at longer SOA (1049 ms—S1: $t_4 = -3.40$, $p < 0.05$; S4: $t_6 = -2.63$, $p < 0.05$; 2000 ms—S1: $t_4 = -5.39$, $p < 0.01$; S4: $t_6 = -4.91$, $p = 0.005$). However, this negative cueing effect or inhibition-of-return was not significant in the group analysis (2000 ms: mean ± SEM = −4.4% ± 4.7%, $t_6 = -0.94$, $p = 0.39$). Subjects maintained their accuracy in reporting the cued grating (mean ± SEM = 93.2% ± 5.8%) and this did not vary with SOA. We also found a significant effect of SOA on the difference between the percentage of cued and piecemeal rivalry reports ($F_{4,24} = 3.95$, $p < 0.05$).

3.3 *Experiment 3*

We found a significant effect of voluntary attention during prolonged periods of binocular rivalry (figure 4). As predicted from previous studies (Levelt 1968), the higher-contrast grating was dominant for a greater proportion of the viewing period than the lower-contrast grating in both conditions (passive: $t_7 = 6.26$, $p < 0.001$; attended: $t_7 = 9.33$, $p < 0.001$). However, we found that the higher-contrast grating dominated for a longer period during the attended condition compared with passive viewing (mean difference ± SEM = 10.6% ± 4.0%; $F_{1,7} = 6.6$, $p < 0.05$). There was no significant effect of target frequency ($F_{2,14} = 1.99$, $p = 0.19$) on dominance of the higher-contrast grating. The number of targets reported in the attended condition (mean ± SEM = 49.7% ± 6.4%) was not significantly different from the passive condition (mean ± SEM = 47.8% ± 8.8%, $t_6 = -0.22$, $p = 0.84$).

The increased predominance for the higher-contrast grating in the attended condition could reflect an increase in the average period of dominance for the higher-contrast grating or a decrease in mean dominance periods for the lower-contrast grating. Figure 5 shows the mean dominance durations for all subjects. Although the average period of dominance for the higher-contrast grating was greater in the attended (mean ± SEM = 5.1 s ± 0.6 s) versus passive (mean ± SEM = 4.6 s ± 0.5 s) conditions, this difference was not statistically significant ($t_7 = -0.84$, $p = 0.43$). In contrast, there

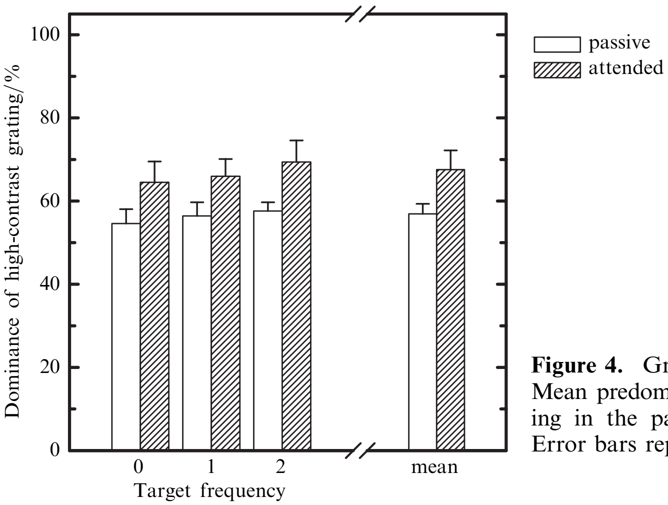

Figure 4. Group data from experiment 3. Mean predominance of the high-contrast grating in the passive and attended conditions. Error bars represent ±1 SEM.

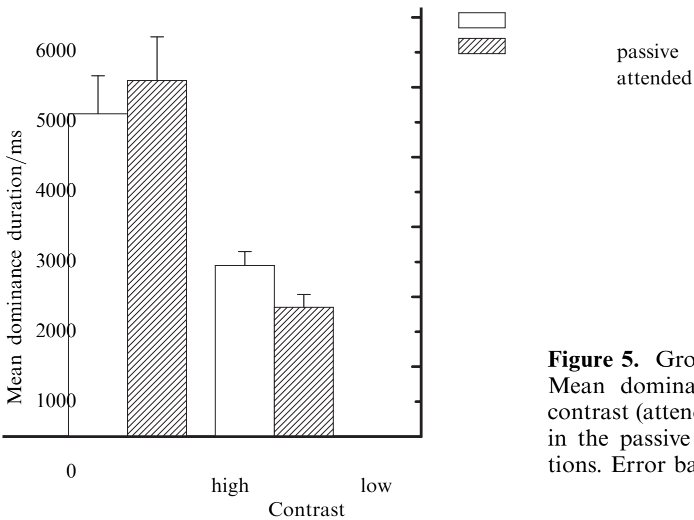

Figure 5. Group data from experiment 3. Mean dominance durations for the high-contrast (attended) and low-contrast gratings in the passive viewing and attended conditions. Error bars represent ±1 SEM.

was a significant decrease in the average period of dominance ($t_7 = 3.79$, $p = 0.007$) for the lower-contrast grating in the attended (mean ± SEM = 1.8 s ± 0.2 s) versus passive (mean ± SEM = 2.5 s + 0.2 s) conditions.

To compare these data with a previous study, we calculated the mean percentage attentional modulation (AM) using the following formula (Meng and Tong 2004): AM = (attended dominance period − passive dominance period)/(passive dominance duration) × 100. We found that the mean AM for the higher-contrast grating was about 10% (mean ± SEM = 11% ± 16%), whereas the AM for the unattended grating was close to −25% (mean ± SEM = −24% ± 5.8%). In their study, Meng and Tong (2004) failed to find a reliable effect of attention with an AM of between ±5% and ±13%.

The passive condition was always performed before the attended condition so an additional analysis was performed to examine the possibility that the difference in conditions may have been due to a learning effect. The total dominance of the high-contrast grating in the first 10 passive trials was compared to the total dominance of the high-contrast grating in the last 10 passive trials for each subject. If a learning effect had occurred we would expect a higher total dominance in the last 10 trials than the first 10 trials. We found no significant difference ($t_7 = -1.05$, $p = 0.33$).

4 Discussion

The aim of this study was to determine how attention is involved in the selection and perpetuation of perceptual dominance during binocular rivalry. We report that involuntary cuing of a grating stimulus prior to binocular rivalry makes the cued stimulus more likely to be perceived. The effect of involuntary attention decreased with an increased interval between the onset of the cue and the onset of binocular rivalry. The time course of this decrease was similar to that found in previous studies of involuntary attention. Finally, we found that perceptual dominance during longer periods of binocular rivalry was influenced by a task that required subjects to voluntarily attend to one of the two competing stimuli. The influence of attention was to decrease the average period of dominance of the unattended stimulus. This result is consistent with voluntary attention increasing the perceived contrast of the attended stimulus.

In the first experiment, we found that a cued grating was more likely to dominate perception during binocular rivalry. With a fixed SOA between the cue and the onset of rivalry, the effect of attention was sustained for up to 2 s. The influence of involuntary attention on the initial selection of a stimulus during rivalry is consistent with previous studies (Ooi and He 1999; Mitchell et al 2004). We also found that short durations of rivalry resulted in fewer reports of complete perceptual dominance and more reports of piecemeal rivalry. In contrast, longer presentation times resulted in more trials that were reported dominant for the cued grating and less piecemeal rivalry. One possible reason for this is that it takes time for attention to be engaged (see Mitchell et al 2004). However, it has been reported that brief rivalry presentations often result in incomplete dominance or even fusion (Wolfe 1983). Therefore, it is also possible that processes underlying rivalry take some time to develop.

In the second experiment, we varied the SOA between the onset of the involuntary cue and the onset of rivalry. The results show that the influence of exogenous attention was maximal at the shortest SOA (~ 300 ms), but that the influence of the cue gradually decreased with time. This result is in good correspondence with a study of Ooi and He (1999) who used pop-out cues, although they did not determine the time course for SOAs over 700 ms. The temporal characteristics of attention in the current study are similar to other experiments in normal vision (Posner and Cohen 1984; Nakayama and Mackeben 1989; Klein 2000). We also found evidence for inhibition-of-return (a bias toward the uncued grating) at longer SOAs (> 1000 ms) in some subjects (see also Posner and Cohen 1984; Tipper et al 1991).

In the third experiment, we measured the effect of voluntary attention on the selection for perceptual dominance during prolonged periods of binocular rivalry. When subjects engaged in a task that required voluntary attention to a particular grating stimulus, the proportion of the viewing period that that grating dominated perception was increased compared to passive viewing. Despite the fact that the overall dominance of the attended grating was greater in the attended condition, individual dominance durations for the attended grating were not significantly greater than during passive viewing. The reason for the increased overall dominance of the attended grating was that the individual periods of perceptual dominance for the unattended grating decreased. This result contrasts with a recent study of Chong et al (2005) who reported that voluntary attention only affected the dominance durations of the attended stimulus. Although the task and stimuli from the two studies show some differences, there are also many similarities. So, it is not clear why these studies have yielded different results. However, our results are consistent with the effect of increasing stimulus strength during binocular rivalry (Levelt 1968). For example, when the contrast of one stimulus is increased during binocular rivalry, it dominates perception for a longer period than the lower-contrast stimulus through a decrease in dominance durations of the weaker stimulus

(Levelt 1968). Our results imply that voluntary attention increased the perceived contrast of the attended stimulus (see also, Carrasco et al 2004; Luck 2004; Treue 2004).

Previous studies have provided conflicting results about the magnitude of the influence of voluntary attention on perceptual dominance during longer periods of binocular rivalry (Lack 1978; Blake 1988; Meng and Tong 2004; Chong et al 2005). In a recent study, Meng and Tong (2004) concluded that there is only a very small effect of voluntary attention on binocular rivalry especially in comparison with the effect on ambiguous figures such as the Necker cube. This was the case even when they use higher-level stimuli and spatially biased rivalry displays that should be more susceptible to the effects of attention. In contrast, our results demonstrated a consistent effect of voluntary attention on binocular rivalry even with simple grating stimuli. One possible reason for a difference between studies could be that in this study, subjects were engaged in an active task, rather than being instructed to attend. Thus, the reduced effects of voluntary attention could reflect a difficulty in focusing attention for sustained periods of time without a task (Helmholtz 1867/1962). Nevertheless, the more marked influence of involuntary attention on binocular rivalry suggests that the inability to sustain attention may not be the only factor.

A possible reason for the difference between involuntary and voluntary attentional modulation of rivalry could be that they are acting at different stages of the process. Binocular rivalry could be expected to have at least two stages, an initial selection stage where competition is determined and one stimlulus is selected for initial dominance, and a later stage where alternations in perception are controlled (Fox 1991; Blake and Logothetis 2002). Because the cue was always presented to both eyes, the effect of attention must occur at the level of stimulus rather than the eye of origin. It is possible that the initial selection for dominance is stimulus-driven (cf Kovacs et al 1996; Logothetis et al 1996; Andrews and Purves 1997) and under the influence of attention. These findings are consistent with other studies that have shown that prior viewing of an adapting stimulus in normal vision influences the selection of that stimulus when viewed during binocular rivalry (Blake and Overton 1979; Blake et al 1980; Wade and de Weert 1986; Ikeda and Morotomi 2000; Pearson and Clifford 2005; Holmes et al 2006). For example, if both eyes briefly view a grating stimulus prior to the presentation of the same grating in one eye and an orthogonal grating in the other, subjects tend to report perceptual dominance of the non-adapted grating (Holmes et al 2006). In contrast, the alternations in perception that accompany longer periods of binocular rivalry could be controlled by an interocular inhibitory mechanism (Blake 1989; Lehky and Blake 1991; Tong and Engel 2001), allowing a more limited influence from selective attention.

In conclusion, we have shown that involuntary attention to an object influences the dominance of that object when it is viewed during binocular rivalry. The effect of involuntary attention on binocular rivalry decreases with a time course that is similar to that found during normal vision. We have also shown that tasks employing voluntary attention can influence the selection of a dominant stimulus during binocular rivalry. The question remains whether the competition during binocular rivalry is an example of a more general attentional mechanism within the visual system (Helmholtz 1867/1962).

Acknowledgments. We would like to thank Lara Pattison for her help during the course of these experiments. We are also grateful to Dan Smith, Nick Wade, and an anonymous reviewer for valuable comments on an earlier version of the manuscript. The work was supported by a grant from the EPSRC to TJA.

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ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 36 2007

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