Endogenous attention prolongs dominance durations in binocular rivalry

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We investigated the effects of attention on dominance durations during binocular rivalry. In a series of three experiments, observers performed several tasks while viewing rival stimuli to ensure and control deployment of attention. We found that endogenous attention can prolong dominance durations of attended stimulus. We developed a novel single-task procedure where observer's responses in an attentional task were used to objectively estimate dominance durations of the attended stimulus. Using this procedure, we showed that paying attention to the stimulus features involved in rivalry is necessary for prolonging dominance durations—mere engagement of attention during rivalry was insufficient. Finally, we were able to simulate the effects of endogenous attention by doubling the contrast of the attended stimulus while it was dominant. Attention may increase the apparent contrast of the attended stimulus, thereby prolonging its dominance duration. Overall, our results indicate that dominance durations in rivalry can be prolonged when observers are performing an attentionally demanding task on the rival stimulus.

Keywords: attention, binocular rivalry, contrast enhancement, dominance duration

Introduction

We live in a busy visual world where potentially important objects and events compete for our limited perceptual resources. This competition is generally resolved through mechanisms that select some stimuli for more focused, refined processing while diverting computational resources from unselected stimuli. This selection process is often dynamic such that different stimuli are selected over time. Visual attention is one example of selective processing: When multiple stimuli compete for representation, attention selects a subset of stimuli for deeper processing. Binocular rivalry also can be construed as involving stimulus selection that changes over time. Binocular rivalry is experienced when different stimuli are presented to two eyes, creating "visual competition" that typically results in the perceptual experiences that fluctuate between alternative interpretations registered by the left and right eyes (Levelt, 1965). Because stimulus selection is a cardinal property of both attention and binocular rivalry, researchers ever since Helmholtz (1925) have hypothesized that these two processes are related.

Helmholtz (1925) observed that he could sustain dominance of one stimulus during rivalry by mentally counting the number of contours present in a given rival target; counting, he assumed, focused attention and thereby sustained dominance. Meredith & Meredith (1962) investigated whether attention can change rivalry alternation rate by giving people different instructions. They found that observers could increase rivalry alternation rate under a "rapid rate" instruction and slowed down alternations under a "slow rate" instruction. Lack (1978) replicated their finding not only in alternation rates but also in dominance durations using afterimages as rival stimuli and in an experiment where intrinsic eye muscles were temporarily paralyzed, thus eliminating potential confounds linked to eye movement and blinks.

van Ee, van Dam, & Brouwer (2005) studied novel stimuli where monocular and binocular depth information indicated opposite 3D interpretations (called slant rivalry) and reported an increase in the dominance duration of the attended 3D interpretation. Slant rivalry, however, is phenomenologically rather similar to bistable 3D stimuli such as Necker cube; thus, it is unclear whether this effect generalizes to more typical rivalry stimuli. Neisser & Becklen (1975) showed observers two different movies either superimposed on one another or presented separately to the two different eyes. Although the latter condition produced binocular rivalry, observers' performance on attending to one of the two movies by doing a task was the same as in the nonrivalry, superimposition condition. This result

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showed that attention could prolong the dominance duration, but two separate tasks for each movie happened in different positions so that one could easily attend to one of the two movies. As a result, observers' performance was essentially perfect (the highest error rates were 4%). Because of nonspatial overlap between the two tasks, binocular rivalry might not have happened in the critical region where observers did the tasks.

Recently, Meng & Tong (2004) showed that although attention can change alternation rates, its effect on dominance duration during rivalry is negligible. They attributed the lack of attentional influence on dominance duration to the possibility that alternation rates could be easily changed due to nonselective nature such as increases in arousal, neural excitation, and the frequency of blinks and microsaccades, whereas dominance durations could not be influenced as much by these factors. This result was shown using complex objects (house vs. face rivalry) that are processed in higher visuals areas and therefore are presumably more susceptible to the effects of attention. This was in contrast with the bistable Necker cube, where attention increased the dominance duration of the attended 3D interpretation. Similar findings were observed when comparing attention's effect on conventional rivalry (orthogonal gratings) versus slant rivalry (van Ee et al., 2005).

Why do some studies find that attention can increase dominance durations of an attended stimulus while others do not? These differences among studies may be due, at least in part, to the lack of systematic control over attentional modulation. In previous studies (Lack, 1978; Meng & Tong, 2004; Meredith & Meredith, 1962; van Ee et al., 2005), attention was modulated simply by an experimenter's instructing observers to attend to one stimulus or the other—observers were not required to perform an attentionally demanding task. Thus, whether selective attention can increase the duration of dominance needs careful investigation under more controlled attentional conditions.

In the present study, we investigated the effects of attention on dominance durations during rivalry using several tasks designed to control the deployment of attention. In a series of three experiments, we found that endogenous attention prolonged dominance durations of an attended stimulus. Furthermore, we showed that paying attention to the stimulus features involved in rivalry is necessary for prolonging dominance duration. Finally, we were able to simulate the effects of endogenous attention by increasing the contrast of attended stimulus while it was dominant.

Experiment 1

We tested whether endogenous attention could increase the dominance duration. Observers paid attention to either one of two gratings or both of the two gratings by monitoring changes in spatial frequency of rival gratings. We compared dominance durations of these conditions with those of passive viewing condition.

Methods

Four individuals, including the first author, participated in this experiment. All had normal or corrected-to-normal visual acuity and good stereopsis. Every aspect of this study was carried out in accord with the regulations of the Vanderbilt University Institutional Review Board.

Stimuli were created using MATLAB in conjunction with the Psychophysics Toolbox (Brainard, 1997) and were presented on the screen of an NEC 21 in. monitor, running on 75 Hz. Observers viewed the monitor through a mirror stereoscope, with the left eye seeing only the left half of the screen and the right eye seeing only the right half of the screen. Effective viewing distance was 96.5 cm; thus each pixel subtended approximately 0.02° of visual angle. The observer's head was stabilized by a chin and forehead rest. Average luminance of the display, including background, was 13.3 cd/m^2. The contrasts of all gratings were 26.8%.

Seven sampled frames of the dichoptic stimulus for each eye are shown in Figure 1. The two obliquely oriented gratings presented to each eye underwent independent changes in their spatial frequencies for 60 s. During this 60-s period, the spatial frequency of the gratings could vary between 1.5 and 8.5 cycles/deg. The initial spatial frequency of the first frame for each grating was near the middle spatial frequency of the possible range (5 + 0.4 cycles/deg). Spatial frequency changed at 0.07 cycles/deg/frame. Spatial frequency tended to continue changing in a given direction, with a probability of direction reversal being 0.2% per frame unless either feature reached an upper or lower limit in which case a change inevitably occurred.

We manipulated attention in three conditions: passive, attended by doing a task on single grating, or attended by doing a task on both of two gratings. There were eight 60-s trials in the first and in the third level of the condition, whereas there were sixteen 60-s trials in the second level to collect approximately the same number of dominance

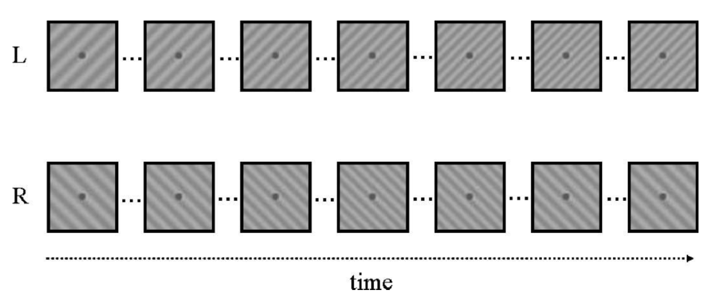

Figure 1. An example of the display used for Experiment 1. Shown here are seven (nonconsecutive) frames showing changes in spatial frequency for each eye. In the actual sequences, changes were smooth and less conspicuous.

durations because in this level only half of dominance durations were collected during the attention task. Stimulus and attention conditions were counterbalanced across eyes.

Prior to each trial, if it is an attended block for a single grating, an on-screen cue specified which one of the two gratings was the target for the attentional task performed by observers during the 60-s period. Observers' task was to report how many directional changes in spatial frequency happened during the 60-s period at the end of the trial. After the instruction, spatial frequency of each grating presented to each eye changed smoothly over time, with the directions of change being independent for the two gratings. During this period, observers tracked periods of exclusive dominance by depressing "1" when they perceived the −45° grating and depressing "2" when they perceived the +45° grating. They pressed neither button when they experienced mixed dominance (i.e., portions of both gratings). At the same time, observers silently counted directional changes in spatial frequency and reported the total number at the end of a trial. Because observers performed the counting task only when the attended stimulus was dominant, the correct response equaled the total number of changes that occurred while the key assigned to the attended stimulus was depressed. On average, 5.9 directional changes in spatial frequency occurred during the 60-s period (standard deviation was 2.8).

Results and discussion

Accuracy in the counting task averaged 71%, implying that the task was sufficiently difficult enough to require sustained attention. Figure 2 shows the main results of Experiment 1. We normalized data to the average dominance duration of the passive condition to account for individual differences in dominance durations (Carter & Pettigrew, 2003).

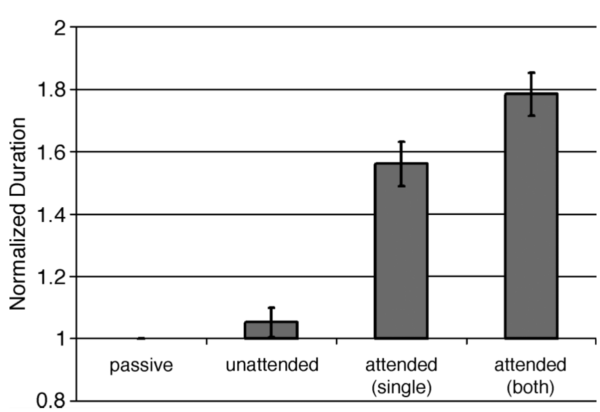

Figure 2. The results of Experiment 1 (means and standard errors for four observers) for passive, unattended, and attended conditions. "(single)" indicates the condition where observers did the counting task on one of the two gratings and "(both)" indicates the condition where observers did the task on both gratings. The *Y*-axis indicates normalized duration.

When observers counted directional changes in spatial frequency in one of two gratings, mean dominance duration increased by about 50% compared to the passive condition. This difference was statistically significant in each individual analysis (p values of independent t test for each observer were all less than .01). Moreover, when observers did the counting task on both of the two gratings, mean dominance durations were also longer than those measured during the passive condition (p value of all four observers was less than .01). However, the difference of dominance duration between the two attending conditions was not different (only two observers showed p value less than .05). Increased dominance durations due to attention are consistent with what Lack (1978) found. However, mean dominance durations of the unattended grating, on which observers did not do the task, was not statistically different from that in the passive condition, $t(3) = 0.54$, $p = .63$; only one observer showed significantly longer durations for the unattended condition than for the passive condition. Hence, endogenous attention prolonged the dominance durations of an attended stimulus but had no influence on the dominance durations of unattended stimulus.

One might surmise the lengthening of dominance durations of the attended stimulus resulted from a bias to report mixed percepts as exclusive dominance when portions of the attended grating were visible. We find this possibility unlikely, however. Because we used small rival stimuli (l°), the overall proportion of mixed dominance was low (on average, 11%). Moreover, the proportion of mixed dominance in the passive condition (13%) did not differ from that in the attended condition (10%), $t(3) = 0.64$, $p = .57$, implying that bias was not the reason for prolonged durations in the attended condition.

We found robust increases in dominance durations when attention was endogenously directed to a given stimulus. However, Meng & Tong (2004), who did not use a task to control attention, did not find increases in dominance durations when observers were simply instructed to attend to one rival stimulus. This difference may well be due to having a task to modulate attention, just like Helmholtz (1925) suggested. If performing the task is indeed critical for prolonging dominance durations of the attended stimulus, then one would expect that better performance in the counting task will be associated with longer dominance durations. A correlation analysis can shed light on this question. We calculated mean normalized dominance durations for the attended stimulus and percent-corrected performance for each 60-s trial and for each observer and correlated these two measures. All four observers had a positive correlation coefficient, average $r = .28$; $t(3) = 4.93$, $p < .05$. To measure more robust percent correct in monitoring changes in spatial frequency, we partitioned all dominance durations into quartiles and computed the averaged percent correct for all trials within each quartile. The correlation coefficient computed from those data was .89. This analysis implies that the better observers did on the challenging task, the longer the dominance durations were in rivalry. Just as

Helmholtz (1925) suggested, performing some kind of mental operation on one of the two rival stimuli is important for prolonging the dominance of that stimulus in rivalry.

Needless to say, correlation analyses alone cannot establish a causal relationship between the task performance and longer dominance durations. One can also surmise that the task is easier because dominance durations are longer. This conclusion, however, cannot explain why dominance durations were longer some trials and shorter in others.

Experiment 2

In the first experiment, endogenous attention prolonged the dominance durations of the attended stimulus, but it did not change the dominance durations of the unattended stimulus. One could argue that this finding arises from biases in observers' tracking behavior, not from changes in the actual durations of dominance. We found no evidence for such biases when comparing the incidence of mixed dominance for attended and unattended conditions, but bias could conceivably operate in other ways too. Moreover, one might worry that the dual-task procedure we used, wherein observers tracked rivalry alternations and monitored changes in one or both rival stimuli, produced spurious changes in dominance durations. To get around these possible objections, we developed a novel single-task procedure that allowed us to track rivalry objectively and, at the same time, measure attentional performance.

Methods

Three individuals, including the first two authors, participated in this experiment.

Stimulus patterns were created in MATLAB with the Psychophysics Toolbox (Brainard, 1997) and Video Toolbox (Pelli, 1997) and shown on a linearized Sony E540 monitor (1600 × 1200 resolution, 85 Hz). Viewing distance was 83 cm (yielding 1 × 1 arcmin per pixel). Observers viewed the monitor through a mirror stereoscope. The luminance of the gray screen background was 61.1 cd/m^2.

Rival stimuli were a concentric oval grating that resembled a bull's-eye (Figure 3, right eye) and a radial checkerboard (Figure 3, left eye), both enclosed within high-contrast, textured frames that served to promote stable binocular alignment. The size of each stimulus was 1° × 1°, and the contrasts of the radial and concentric gratings were 23% and 33%, respectively. These contrasts yielded approximately equal dominance durations for the two stimuli. During 90-s observation periods, the rival target containing the concentric grating underwent both a *shape* change and a *shading* change (Figure 3). The shape change involved varying the aspect ratio of the oval grating between one of two values corresponding to a slightly

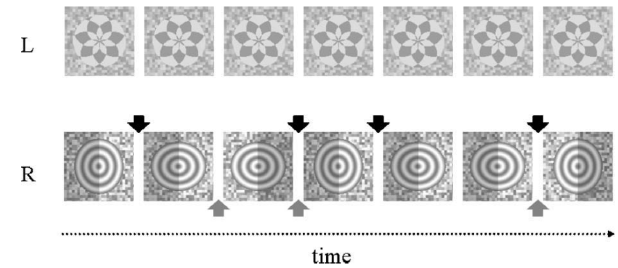

Figure 3. Rival stimuli for Experiment 2. In the left eye, a control stimulus is shown (a radial checkerboard) and a concentric grating stimulus is shown (a bull's-eye pattern) in the right eye. The concentric rival target changed over time unpredictably. In this schematic, dark arrows denote times when shape changed and light arrows denote shading changes. Each frame is meant to represent 1 s. Observers pressed one of two buttons to track changes in shape or changes in shading, demanding tasks that require sustained attention. For illustration purposes, the magnitudes of the shape and shading changes are greatly exaggerated.

elliptical figure whose long axis was horizontal and one whose long axis was vertical. The shading change involved switching of the slightly darkened (shaded) half of the image from side to side. This shading manipulation generated the compelling impression that one-half of the oval object was covered by a weak neutral density filter, with the position of the filter jumping from side to side unpredictably.

The shading and shape changes were uncorrelated and could occur at 1-s intervals (i.e., at 1, 2, 3, 4 s, etc., after the beginning of the experimental run). The probability of each type of change occurring was .7, thus yielding on average 63 changes per 90-s trial. The changes themselves were quite subtle and occurred smoothly over a 250-ms interval, thereby avoiding abrupt transients. The magnitude of change was adjusted for each observer to yield detection performance between 75% and 90% during nonrival, monocular testing. Thus, these dynamic stimulus changes were sufficiently small that sustained attention was required to accurately track the changes. Furthermore, while tracking either shape or shading change, the other type of the change was largely inconspicuous.

There were three different conditions/tasks: conventional rivalry tracking (passive condition), shape change tracking, and shading change tracking. The only difference between conditions was the task; the stimulus conditions, in other words, were always the same in all conditions. In the conventional rivalry tracking condition, observers were instructed to simply press and hold a key when the concentric grating was visible. In the shape and shading conditions, observers tracked either shape or shading "state" by pressing and holding one of two keys; observers pressed neither key when the oval grating was suppressed. To extract each observer's performance, the correctness of observer's key press was evaluated at 1-s intervals. For the key press to be counted as correct, it had to match the stimulus state from the previous second. These same key presses were also used to estimate dominance durations of the concentric grating (because observers could track stimulus changes only while concentric grating was dominant). To ensure that brief key releases that inevitably occurred when observers switched keys in response to a stimulus change are not counted as rivalry alternations, all such periods shorter than 300 ms were ignored for purposes of indexing rivalry state. To verify that this technique yields accurate estimates of dominance durations, we performed a pilot experiment where observers viewed a display that physically alternated between two stimuli and at the same time, tracked either shape or shading change when the concentric grating was visible. Dominance durations extracted from stimulus tracking data were comparable (97.8 ± 1.1%) to the actual visibility durations of the concentric grating. This 2% difference between extracted and actual dominance durations translates to dominance durations that are, on average, 86 ms shorter—more than an order of magnitude smaller than the effect reported in this experiment. This small, but consistent, difference is most likely due to the longer choice reaction time associated with the stimulus tracking task. That is, observers had to decide which key to press when the concentric grating became dominant—a process that lengthens reaction times (Donders, 1868).

Each observer ran at least six 90-s trials in each condition. One observer (SC) ran a larger number of trials (10) because his dominance durations are typically long (9–12 s), thus reducing a number of data points from a 90-s trial. Both the eye receiving the oval grating and the order of conditions were counterbalanced for each observer.

Results and discussion

Overall performance in the two tracking tasks was 89%, indicating that the task was sufficiently difficult to require sustained attention. For each individual observer, dominance durations in two of the stimulus tracking conditions were normalized relative to the mean dominance duration in the passive condition. The average of these data is shown in Figure 4. The dominance of the control stimulus was not affected by attentional tasks directed to the other rival target (only one observer showed significantly higher durations for the control stimulus when he did the shape task than when he did not do the task). This is in agreement with results from Experiment 1 and indicates that attending to one rival target does not affect dominance durations of the other rival target. Moreover, this result provides additional supporting evidence that this new method can accurately track perceptual alternations of rivalry. However, attending to the concentric grating did prolong its dominance duration by almost 50%, but only when attention was directed toward the rival target's shape (data for all observers showed p value less than .05). This

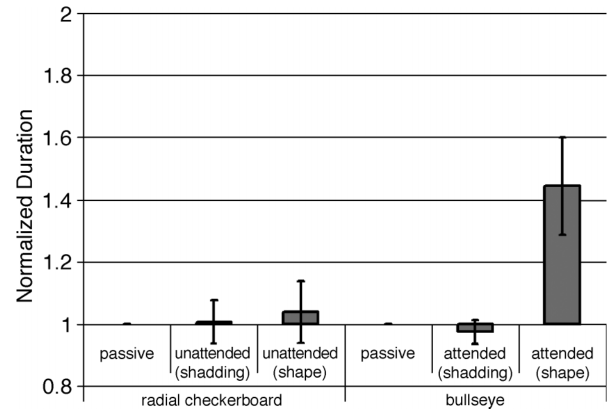

Figure 4. The results of Experiment 2 (means and standard errors for three observers) for passive, unattended, and attended conditions. The label "(shading)" indicates the condition where observers did the shading task and "(shape)" indicates the condition where observers did the shape task.

difference is best understood in the context of different task demands for two stimulus tracking conditions. To accurately track shape changes, observers directed attention to the concentric grating itself, the object undergoing rivalry. In the shading task, however, observers reported that good performance required paying attention to global change in shading, and to do this they tended to ignore the concentric grating. We suspect that the critical difference between the conditions was that in the shape tracking condition observers paid attention to the very feature involved in rivalry. In contrast, in shading tracking condition, the attention was directed to the same location in space but not to circular grating per se.

In summary, Experiment 2 shows qualitatively similar results to those found in Experiment 1, although observers did not perform a dual task: attentional tracking and rivalry tracking were obtained from the same task objectively. We found that directing attention to the visual feature prolonged its dominance duration while having no effect on its suppression duration. In addition, Experiment 2 shows that mere engagement of attention during stimulus dominance is not sufficient to affect dominance durations. This latter result is consistent with Chong & Blake's (2005) finding that endogenous attention effect was reduced when attention was directed to nonrival features.

Experiment 3

By what means does endogenous attention increase dominance durations of rivalry? Previous work on visual attention suggests that attention can increase the effective contrast of a visual pattern (Carrasco, Ling, & Read, 2004; Lu & Dosher, 1998). Moreover, Chong & Blake (2005) showed that the attentional boost in initial tendency for dominance was of the same magnitude as that predicted by an actual contrast boost. Endogenous attention may increase the dominance duration of the attended stimulus by increasing its apparent contrast.

According to Levelt's (1965) second proposition, however, increased strength in one eye does not change the mean dominance duration of that eye but decreases the mean dominance duration of the other eye. Contrary to this proposition, our previous two experiments showed that endogenous attention increased dominance durations of an attended stimulus, but it did not change the durations of an unattended stimulus. We hypothesized that endogenous attention operates to increase contrast of a stimulus only when that stimulus was dominant. To test this hypothesis, we simulated the putative effect of attention by physically increasing the contrast of the attended stimulus only when it became dominant. We compared mean dominance durations from this simulation with those produced when actually performing an attentional task.

Methods

Three individuals, including the first author, participated in this experiment. The apparatus was the same as in Experiment 1.

The two obliquely oriented gratings were presented to each eye. One of them underwent changes in its spatial frequency for 60 s just like Experiment 1. The parameters of the changes in spatial frequency were exactly the same as those used in Experiment 1. The other rival grating flickered in counter phase at 2.7 Hz. The contrast levels of this grating were ramped up and down smoothly from 89% to 0% with reversals in direction of change synchronized with the zero-crossing of the counter-phase flicker.

To simulate attention's putative effect, we gradually doubled the contrast of one of two gratings over 520 ms whenever observers reported that this grating was dominant. Note that this modulation should not engage exogenous attention, because the change in contrast did not produce transients satisfying the fast-decay time constant of exogenous attention (Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989). We elected to double the contrast because that was the approximate magnitude of attention's effect in Experiments 1 and 2 as well as in earlier studies of attention and initial selection in rivalry (Chong & Blake, 2005). As soon as observers reported a switch in the dominant stimulus back to the flickering grating, we smoothly reduced the contrast of the attended grating over 520 ms back to its original level.

There were three conditions in this experiment: passive viewing, attention directed to the task-relevant grating whose spatial frequency was changing, and contrast increase introduced at the onset of dominance of the grating whose spatial frequency was changing but not being monitored. There were eight 60-s trials devoted to each of the three conditions, which were administered in blocks. The eye receiving the attended grating was counterbalanced over trials within each block.

The procedure was as same as in Experiment 1 except that observers did not do the counting task when attention was simulated by increasing the contrast of the attended grating. They simply tracked perceptual alternations during rivalry.

Results and discussion

Performance in the counting task was on average 67%. Figure 5 shows average normalized dominance durations for each condition.

When observers counted directional changes in spatial frequency in one of two gratings, mean dominance durations increased by 50% compared to durations measured during the passive condition. This difference was statistically significant on each individual analysis (p values of independent t test for each observer were all less than .01). However, mean dominance durations of the unattended grating, on which observers did not do the task, were not statistically different from those in the passive condition, $t(2) = 1.4$, $p = .30$; only one observer showed significantly increased dominance durations for the unattended condition as compared to the passive condition. Qualitatively similar results were found for the contrast increment condition: when the contrast of the attended grating was increased during its dominance period, mean dominance duration was increased by a factor of 1.29 as compared to the passive condition (p values of independent t test for each observer were all less than .05). Mueller & Blake (1989) found a similar effect (a factor of 1.22) when they synchronously doubled the contrast of a grating, but only when it was dominant. However, mean

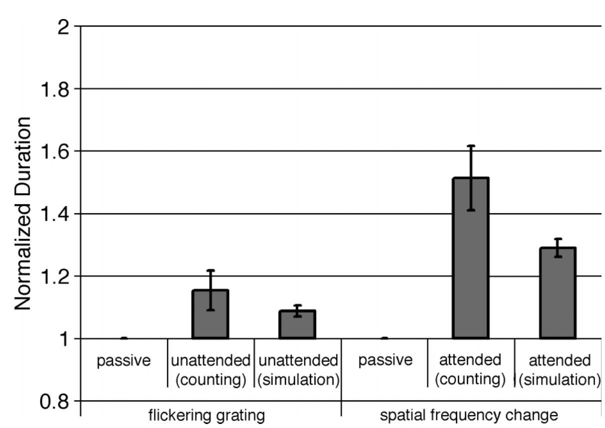

Figure 5. The results of Experiment 3 (means and standard errors for three observers). "(counting)" indicates when observers did the counting task and "(simulation)" indicates simulation.

dominance durations of the unattended grating were not different from that of the passive condition, $t(2) = 2.88$, $p = .10$; no observer showed significant difference in the individual analysis. The proportion of mixed dominance in the passive condition (17%) did not differ from that in the attended condition (12%), $t(2) = 1.28$, $p = .33$.

Although the effect size of attention was smaller in the simulation (1.29 times) compared to that in the attended condition (1.51 times), we qualitatively showed the same pattern of results between the two conditions; attention increased dominance durations of the attended stimulus, but not of the unattended stimulus. The failure of the simulation to mimic quantitatively the actual attention effect could simply result from our using an insufficiently large contrast increment. Do our results violate Levelt's (1965) proposition stating that contrast variations in one eye's rival target primarily affect the dominance durations of the other eye's target? Perhaps not. It is worth noting that in our Experiment 3 (and in Mueller & Blake, 1989) increases in contrast were introduced during ongoing rivalry, whereas Levelt's proposition (1965) was developed to explain rivalry dynamics under conditions where contrast values remain invariant during an observation period. Attention's boost to dominance, which we attribute to an increase in effective contrast, applies only when that stimulus is dominant whereas a physical increase in contrast can affect suppression durations, too.

General discussion

The magnitude of attention's effect on the temporal dynamics of binocular rivalry has been controversial (Helmholtz, 1925; Lack, 1978; Meng & Tong, 2004; Meredith & Meredith, 1962; van Ee et al., 2005). Our study provides a potential resolution to this controversy by introducing an explicit attentional task during the rivalry observation period. We found that observers' performance on this demanding task was positively correlated with the duration of dominance. However, when observers did not perform a task requiring attention, the average durations of dominance did not increase (Meng & Tong, 2004). Furthermore, we showed that attention prolonged dominance durations only when attention was directed to a rivalry-relevant feature, not just to a stimulus characteristic imaged at the same spatial location—simply performing a task to induce attention was not sufficient for prolonging dominance durations. Finally, we successfully simulated the effect of attention by increasing the physical contrast of the attended stimulus, only when it was dominant.

How is it that attention can prolong the dominance durations of an attended stimulus? We know that attention can bias the initial selection in rivalry toward the attended stimulus (Chong & Blake, 2005; Mitchell, Stoner, & Reynolds, 2004; Ooi & He, 1999). Chong & Blake (2005) suggested that attention increases the apparent contrast of attended stimulus by about 0.3 log units, thereby increasing its chances of becoming dominant in the initial phase of rivalry. Just as with initial selection, attention may have increased the apparent contrast of the attended stimulus, thereby increasing its duration of dominance. Consistent with this hypothesis, dominance durations of a rival stimulus were prolonged when we increased the contrast by about 0.3 log units, although dominance durations in this simulation condition were not prolonged as much as they were when attention was directed to a stimulus. A larger contrast increment no doubt could more accurately mimic attention's effect.

However, this simulation results are inconsistent with what Levelt (1965) found. He found that increasing the contrast of one rival stimulus did not increase the dominance duration of stimulus with the higher contrast, rather it decreased the duration of the stimulus with lower contrast. This inconsistency between our results and his was due to the fact that attention could increase the contrast of the attended stimulus only when it was dominant. One cannot pay attention to a stimulus when it is invisible. Our simulation results support this claim. Moreover, Mueller & Blake (1989) found similar results not only in qualitatively similar way but also in effect size.

In Experiment 2, we introduced a novel paradigm in which valid records of perceptual alternations during rivalry are derived without relying on observers' subjective reports. Using this technique, we found a lengthening of dominance durations attributable to endogenous attention comparable in magnitude to that found with conventional tracking. This new technique offers a promising, alternative means for studying dynamics of binocular rivalry unconfounded by bias or expectations, and there is no reason this technique could not be applied successfully in any nonhuman species that can be trained to track changes in some characteristic of one of two competing stimuli.

Aside from demonstrating a robust effect of attention on dominance durations, do our results have any bearing on the nature of the processes underlying binocular rivalry? For some years, investigators actively debated whether rivalry was an "early" process based on inhibitory interactions among monocular neurons (e.g., Blake, 1989; Sugie, 1982) or, alternatively, a "late" process stemming from competition among alternative object descriptions (e.g., Logothetis, Leopold, & Sheinberg, 1996; Walker, 1978). More recently, however, this dichotomy has coalesced into a hybrid model in which rivalry is seen to comprise multiple processes distributed throughout the visual hierarchy (Blake & Logothetis, 2002; Wilson, 2003). On this view, attention could plausibly modulate the strength of neural signals at multiple stages of processing, effectively boosting the strength of one of two competing neural representations. It is noteworthy that attention, at least endogenous attention, only affects the durations of dominance of a stimulus. One could imagine a scenario wherein attention continued to operate on the neural representation of a stimulus during suppression, abbreviating its period of invisibility relative to conditions where endogenous, task-driven attention is not being deployed. Indeed, in dichotic listening people can attend to a salient spoken word within an otherwise ignored message delivered to one ear (Cherry, 1953). Consistent with earlier work (Blake, 1988), we find no evidence for attention's fingerprints within periods of suppression, implying that observers must be visually aware of a stimulus in order for attentional resources to be directed at that stimulus.

In summary, we found that attention could prolong the dominance durations of an attended stimulus only when observers paid attention to rival features by doing a task. Attention may increase apparent contrast of the attended stimulus, thereby prolonging the dominance duration.

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