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The separation of monocular and binocular contrast

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ABSTRACT

The contrast asynchrony is a stimulus configuration that illustrates the visual system's separable responses to luminance and luminance contrast information (Shapiro, 2008; Shapiro et al., 2004). When two disks, whose luminances modulate in phase with each other, are each surrounded by a disk, one light and one dark, observers can see both the in-phase brightness signals and the antiphase contrast signals and can separate the two. Here we present the results of experiments in which observers viewed a similar stimulus dichoptically. We report that no asynchrony is perceived when one eye is presented with modulating disks and the other eye is presented with the black and white surround rings, nor is an asynchrony perceived in gradient versions of the contrast asynchrony. We also explore the "window shade illusion" (Shapiro, Charles, & Shear-Heyman, 2005) dichoptically and find that when a modulating disk is presented to one eye and a horizontally split black/white annulus is presented to the other, observers perceive a "shading" motion up and down the disk. This shading can be seen in either direction in the binocular condition, but it is almost always seen as moving towards low contrast in the monocular condition. These findings indicate the presence of separable retinal and cortical networks for contrast processing at different temporal and spatial scales.

1. Introduction

The image in Fig. 1 shows five white disks of the same luminance level but situated on different backgrounds: the disk on the left is placed on a black background, while the backgrounds for the other disks become successively brighter, from the left to the right. Much has been written about the observation that the five disks appear to be different shades of white even though they have the same luminance level (Gilchrist, 2006; Kingdom, 1997). Here we concentrate on an equally noticeable pair of observations: (1) all the disks appear some shade of white; and (2) the disk on the left has highest contrast relative to the background, while the disk on the right has the lowest contrast relative to the background. These two observations suggest that the visual system has methods of encoding information that corresponds roughly to the absolute level of the disks (hence the white appearance) and to the contrast of the disk relative to the background (hence the change in perception induced by contrast). The distinction between contrast and brightness has long been noted, although attention to this important distinction seems to cycle through the literature (see Whittle, 2003 for review). Lately, however, the functional significance of the separation has increasingly become apparent (see Brown, 2003; Frazor & Geisler, 2006; Geisler, Albrecht, & Crane, 2007; Johnson, Hawken, & Shapley, 2008).

Shapiro et al. (2004, 2005) and Shapiro (2008) created a stimulus paradigm for separating a perceptual response to luminance from a perceptual response to contrast. This paradigm—referred to as a contrast asynchrony—is illustrated in Fig. 2 (see Shapiro, Charles, & Shear-Heyman, 2005, supplementary material Fig. 1a). In the basic version of the contrast asynchrony, the luminance levels of two physically identical disks modulate sinusoidally in time (i.e., they change from light to dark and back again); a white ring surrounds one disk, and a black ring surrounds the other. Contrast asynchronies "work" because they juxtapose the temporal phase of two types of information: the luminance levels of the two disks, which modulate in phase, and the contrast between the disks and the surrounds, which modulate in anti-phase. As has been documented extensively (Shapiro, 2008; Shapiro et al., 2004; Shapiro, Charles, & Shear-Heyman, 2005), observers are capable of seeing both the luminance information and the luminance contrast information; that is, observers can perceive that the disks become light and dark at the same time (a perception corresponding to the luminance modulation), yet also perceive the disks to alternate in time (a response corresponding to luminance contrast information).

Shapiro (2008) presented a model that can account for the disappearance of contrast asynchronies at orthogonal angles in color space: the model contains a fast and rectified contrast pathway

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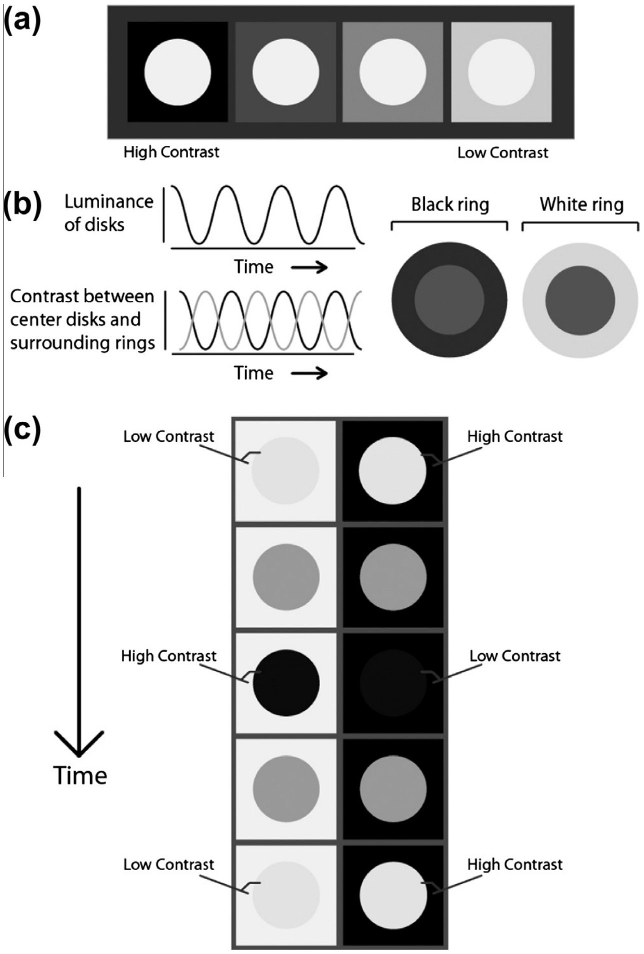

Fig. 1. (A) Four disks of the same luminance level on different backgrounds. There are two different aspects of the display: The disks all appear white; the contrast between disk and surround changes from high to low. The contrast asynchrony juxtaposes these two aspects of the display. (B) The contrast asynchrony stimulus configuration as demonstrated by Shapiro et al. (2004). The luminance levels of the two disks modulate sinusoidally in time; the luminance levels of the disks are always identical to each other. The contrast between the disks and the surrounding fields modulate asynchronously (i.e., when contrast is high between one disk and ring, the contrast is low between the other disk and ring). Observers are able to perceive both the synchronous luminance information (the disks appear to get bright and dark at the same time) and the asynchronous contrast information (the disks also appear to alternate and modulate out of phase with each other). The configuration therefore allows for the separation of the visual response to color from the visual response to color contrast. (C) Five frames of the temporal modulation of the disks in the contrast asynchrony stimulus. The luminance levels of the center disks are identical to each other in each frame; in each cycle the disks change from white to black and back again. The contrast information on the left modulates out of phase with the contrast information on the right. (For interactive demonstration, see http://www.journalofvision.org/content/5/10/2/suppl/DCSupplementaries Figure 1a)

and a slow color appearance pathway. The fast and rectified pathway seems to account for asynchronous appearance, while the slow pathway is the more general one that is typically investigated in studies of brightness, lightness, or color induction (e.g., De Valois et al., 1986; Krauskopf, Zaidi, & Mandler, 1986). The interaction between these two types of pathways is complicated. On the one hand, the perception of the asynchrony can be independent of the perception of brightness: for instance, it is possible to eliminate the perceived asynchrony while not affecting the brightness of the central field (see Shapiro, Charles, & Shear-Heyman, 2005; Fig. 10a; and Shapiro & Leaver, 2010). On the other hand, in some circumstances, contrast asynchronies can lead to changes in brightness (Shapiro, Charles, & Shear-Heyman, 2005).

An example of the visual system's multifaceted response to contrast can be seen in the window-shade/rocking-disk illusion (Shapiro, Charles, & Shear-Heyman, 2005), shown in Fig. 2. In the display, a ring, split so that its top half is white and its bottom half is black, surrounds a single uniform disk. As the luminance of the disk modulates in time, the contrast levels between the disk and the top and bottom portions of the ring alternate: when the disk is bright, the contrast between the disk and the top of the ring is low, and the contrast between the disk and the bottom of the ring is high; and vice versa when the disk is dark. Two separable effects can be discerned in this configuration. The rocking-disk illusion occurs when the ring is thin: the disk appears to bounce up and down in a manner similar to the "phenomenal phenomena" of Gregory and Heard (1983). The window-shade illusion occurs when the ring is thick: motion appears to spread across the disk, as if a window shade were being pulled up and down across the surface of the disk. Shapiro, Charles, and Shear-Heyman (2005) showed that the contrast that produces rocking occurs independently of the contrast that produces shading; the contrast that produces rocking occurs only when the ring is thin (it disappears when the ring is greater than about 10 min of visual angle), and the contrast that produces shading becomes stronger as the ring increases in thickness, suggesting that the mechanism(s) responsible for producing shading can integrate over a very large (>10 deg) area. Shapiro and Knight (2008) showed other examples of how contrast near the border of an object can create responses that hide salient responses to contrast that occur at larger spatial scales.

Investigations with the contrast asynchrony stimuli therefore indicate that similar contrast information can generate different perceptual interpretations, and it seems reasonable to hypothesize that these perceptual interpretations correspond to contrast calculations produced at different stages of visual processing. Here, we address a very basic empirical question that will help determine where and how these contrast calculations occur: Are the contrast responses in the contrast asynchrony available to the visual system under dichoptic viewing conditions? That is, can the alternation or shading seen under normal viewing conditions be perceived when the disks are viewed with one eye while the backgrounds are viewed with the other eye? If the asynchrony can be observed, then the contrast signal originates after the combination of signals from the two eyes (presumably in the visual cortex); if the asynchrony cannot be observed, then perception is dominated by monocular contrast, which presumably originates in the retina.

In this paper we investigate the two-field (Fig. 1) and one-field (Fig. 2) contrast asynchronies in binocular conditions. We find that the two-disk contrast asynchrony response cannot be found dichoptically, whereas the shading percept in the one-disk asynchrony can be produced dichoptically. The results are consistent with other reports that suggest a fast contrast response originating in the retina and a slow contrast response originating in the cortex (Liu & Wandell, 2005; Mullen, Thompson, & Hess, 2010) and with

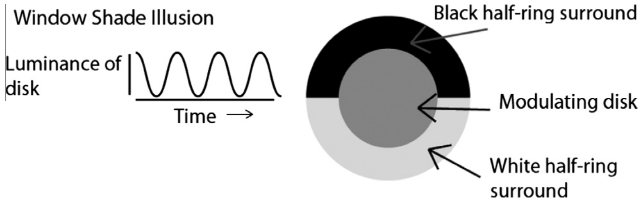

Fig. 2. The Window Shade Illusion, as demonstrated by Shapiro et al. (2004). The luminance level of the center disk modulates sinusoidally in time. Observers perceive a "veil" resembling a window shade that travels vertically across the disk. This veil is created by the contrast between the disk and surrounding edges. (For interactive demonstration, see http://www.journalofvision.org/content/5/10/2/suppl/DCSupplementaries Figure 1b)

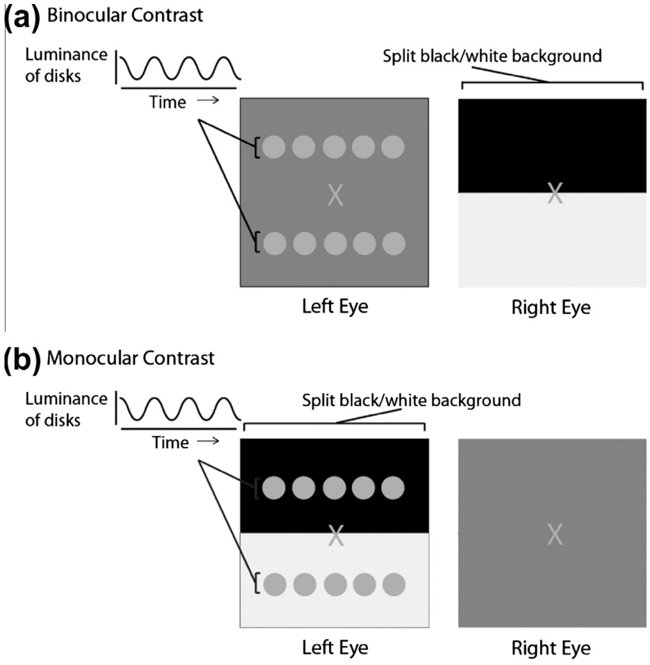

Fig. 3. The stimulus configuration used in Experiment 1. Panel A shows a binocular contrast condition, where the temporally modulated disks are presented to one eye while a split black/white surround is presented to the opposite eye; observers can perceive the contrast asynchrony in this condition only if contrast is created after the combination of images from both eyes. Panel B shows the monocular contrast condition: one eye is presented with two rows of disks and a split black/white background while the other eye is presented with a mid-luminance display.

reports that there are retinal-level and binocular mechanisms for color induction (Shevell, Holliday, & Whittle, 1992).

2. Experiment 1

The first experiment tested whether the contrast asynchrony can be perceived with binocular contrast (i.e., when one eye is presented with the luminance-modulated center, while the other eye is presented with static black and white surrounding fields). The experiment uses the task of Shapiro et al. (2004), which measures the proportion of trials during which observers perceive the disks as modulating asynchronously as a function of modulation amplitude.

2.1. Methods

2.1.1. Apparatus and calibration

The experiments were presented on a CRT monitor (Sony Trinitron Multiscan G520) using a computer running Windows 7. The luminance levels of the monitor were measured using a Spectrascan 650, and gamma was corrected using the driver software packaged with the computer graphics card (Catalyst Control Center on ATI Radeon HD 5970). Linearity and temporal response were checked with a photocell and oscilloscope. The mean luminance was 50 cd/m^2 , and the refresh rate of the monitor was 85 Hz. The stimuli were developed in Adobe Flash CS5. The data from the experiment were automatically saved in files on the computer.

Observers viewed the monitor from a physical distance of 27 cm. The display was viewed through a stereoscope (SA200, ASC Scientific), which created an optical distance of 31 cm. The

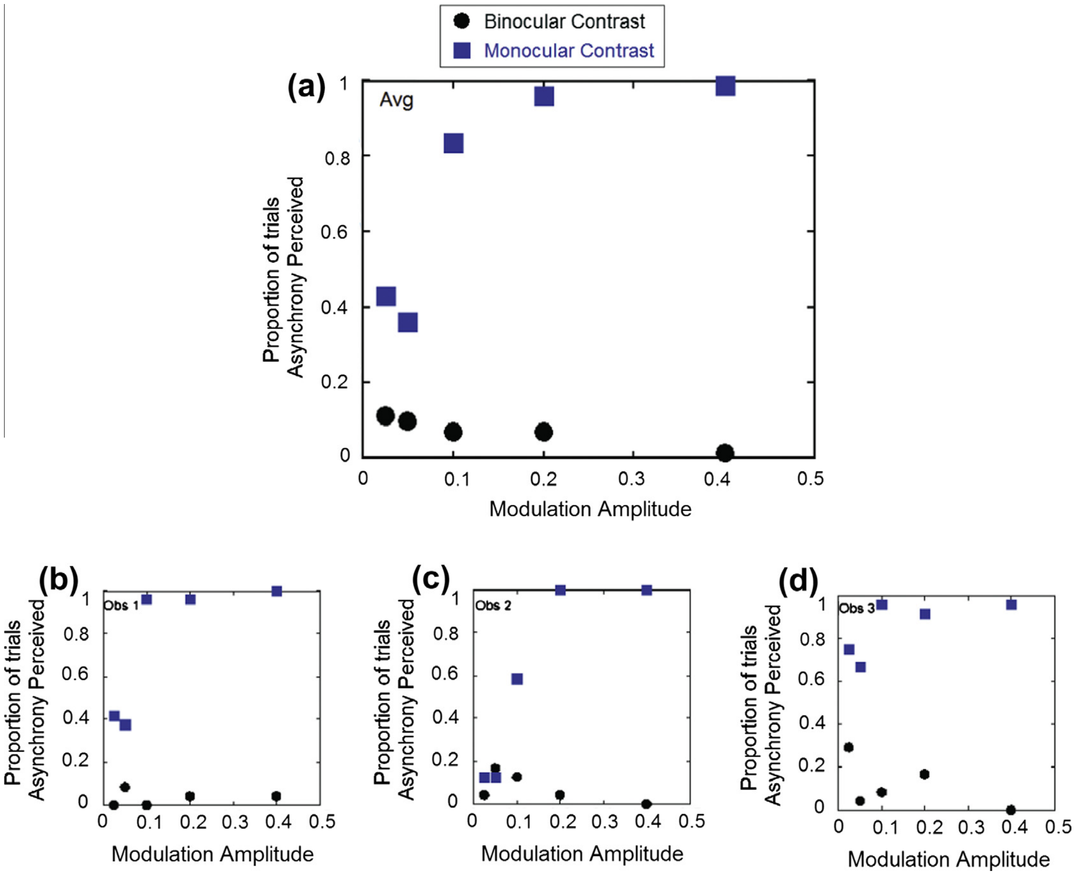

Fig. 4. Data from Experiment 1. At higher luminance modulation amplitudes in the monocular condition, observers were able to perceive the contrast asynchrony in over 80% of trials. Observers were unable to perceive the contrast asynchrony in binocular conditions.

stereoscope was mounted to the monitor to maintain viewing distance, but it could be moved up and down to fit to viewers' different face sizes. The observers were stabilized by a chin rest and responded by pressing buttons on a computer keyboard.

2.1.2. Stimulus configuration

Fig. 3 displays the conditions for Experiment 1. In the binocular contrast condition (panel A), two rows of gray disks are presented to one eye, and a split black/white surround is presented to the opposite eye. The disks modulate in lightness between black and white according to a sine wave function. The disks in the top row are combined with the black background, and the disks in the bottom row are combined with the white background; as a result, observers would be able to perceive the contrast asynchrony only if contrast is created after the combination of images from both eyes. In the monocular contrast condition (panel B), one eye is presented with two rows of disks and a split black/white background, while the other eye is presented with a mid-luminance gray display. In half the trials, the disk is presented to the right eye, and in the other half, the disk is presented to the left eye.

In both conditions, the disks were 1.4 deg of visual angle; the row of five disks covered 9.67 deg. The backgounds were 15.85 deg. A 2.3 deg X in the middle of the screen assisted in binocular fusion of the image. Rows of five disks were used for consistency with Experiment 2. The disks were modulated at 3 Hz; they had a mean luminance level of 50 cd/m^2 and maximum and minimum value of 50 ± modulation amplitude * 100 cd/m^2. The luminance level of the solid background was 50 cd/m^2, and the split backgrounds were 1 and 100 cd/m^2.

2.1.3. Observers

The observers were three university students in their early 20s with normal or corrected-to-normal vision. Two were female, and one was male. Two of the participants were naïve to the aims of the study; observer 1 was an author of this paper (OJF). All three observers reported no difficulty in fusing the two images with the aid of the stereoscope.

2.1.4. Procedure

There were three different variables: monocular vs. binocular contrast; left or right eye presentation of the modulating field; and modulation amplitude (five levels). Each condition was presented 12 times. In total, therefore, there were 240 ($2 \times 2 \times 5 \times 12$) trials. The conditions were presented in a randomized order. Observers pressed one of two keys on the computer keyboard to indicate whether they perceived the disks as modulating out of phase with each other (i.e., did they perceive the contrast asynchrony). Observers were given unlimited time to respond; after each response, a beep indicated a registered response, and the rings and disks were removed for 200 ms.

2.1.5. Results and discussion

Observers reported perceiving asynchronous modulation in the monocular contrast condition but not in the binocular condition. Fig. 4 plots the proportion of trials reported as out of phase as a function of modulation amplitude of the disks. The blue squares represent the monocular contrast condition, and the black disks represent the binocular contrast condition. Panel A shows the average of the three observers' results. In the monocular contrast condition the proportion of trials seen as out of phase increases with modulation amplitude, and in the binocular contrast condition fewer than 10% of the trials were seen as out of phase for all amplitudes. Panels B–D show the results for individual observers. All three observers showed trends similar to the average data. In the monocular contrast condition, the increase in proportion of trials seen as out of phase as a function of modulation amplitude replicates the results of Shapiro et al. (2004) and Shapiro, Charles, and Shear-Heyman (2005).

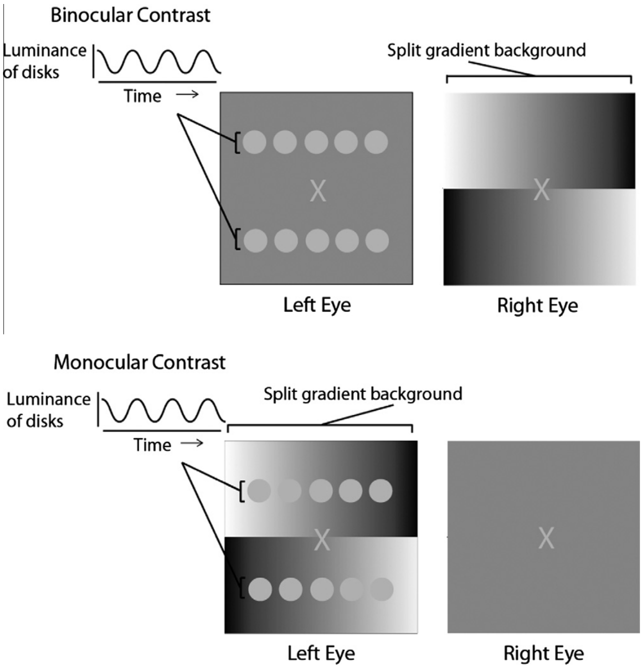

Fig. 5. The stimulus configuration used in Experiment 2. This configuration is the same as in Experiment 1, except that the split black and white background is replaced by horizontal black-white gradients that run in opposite directions. The luminance of the disks modulates in synchrony. Shapiro, Charles, and Shear-Heyman (2005) and Knight and Shapiro (2008) showed that in the monocular contrast condition, motion tracks the point of zero contrast between the disks and the background (i.e. as the disks modulate in luminance, there will be a point when the disk matches the luminance of the neighboring background; this zero-contrast point will occur at different time for different dots since the background is a gradient. Motion will move back and forth tracking the zero-contrast points—see Shapiro and Hamburger (2007) for a demonstration http://www.perceptionweb.com/perception/misc/p5733/2.swf).

3. Experiment 2

Shapiro, Charles, and Shear-Heyman (2005); Shapiro (2008) showed a wide variety of contrast asynchronies. In one example, a row of disks was presented on a gradient background: as the disks modulated from light to dark, the contrast between the disks and the dark part of the gradient modulated in antiphase relative to the contrast between the disks and the white part of the gradient. The modulation created a perception of motion that shifts back and forth across the grating, tracking the point of zero contrast between the disks and the background (i.e. where a disk and its neighboring background are the same shade of gray). For examples see Fig. 6a in demonstration page for Shapiro, Charles, and Shear-Heyman (2005) (link: http://www.journalofvision.org/content/suppl/2011/01/04/5.10.2.DCSupplementaries/5.10.2_supplement.html or the demonstration Fig. 2 in Shapiro & Hamburger, 2007 http://www.perceptionweb.com/perception/misc/p5733/2.swf).

Here we examine whether observers can perceive contrast-generated motion in binocular conditions. The purpose of the experiment is twofold: 1. The experiment gives a second test of Experiment 1, but here the contrast between the disks and gradient background generates a motion signal, so instead of an asynchrony observers see motion drifting back and forth across the screen. 2. As expressed at the end of Experiment 1, it is possible that the combination of the disks with the white and black

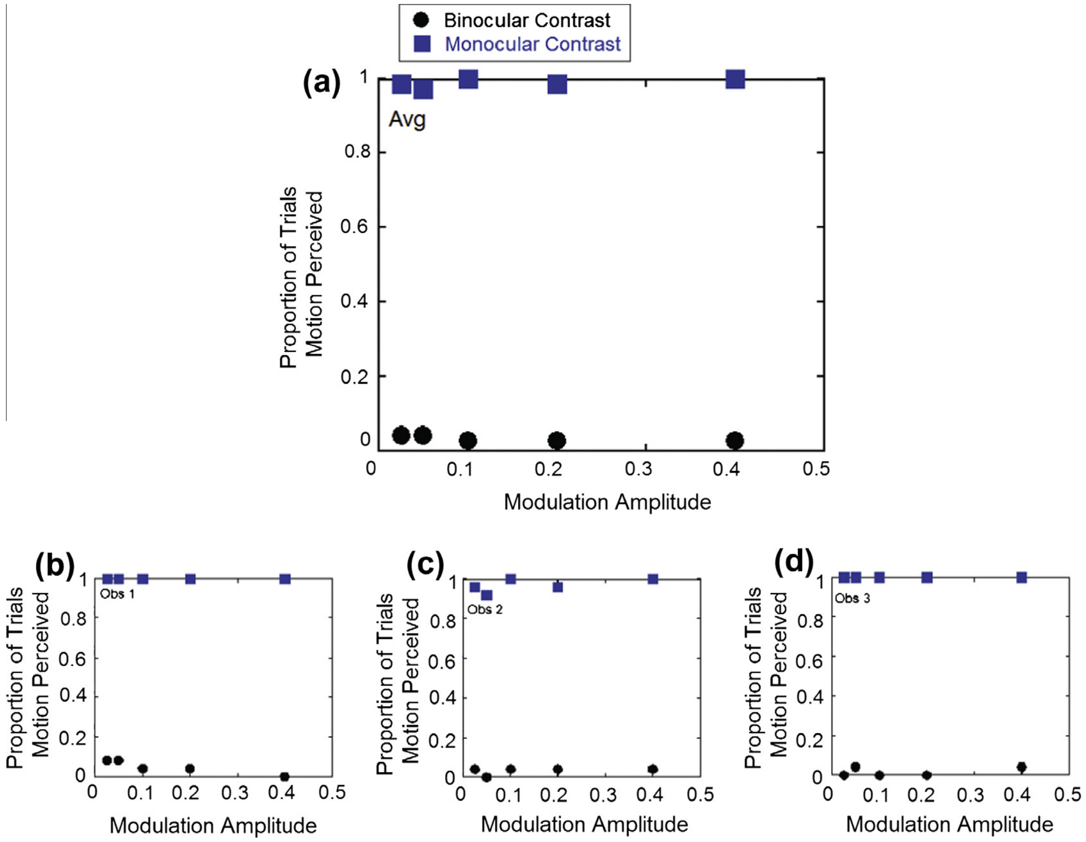

Fig. 6. Data from Experiment 2. In the monocular condition, observers perceived the contrast-generated motion in almost all trials. In the binocular condition, observers failed to perceive the motion.

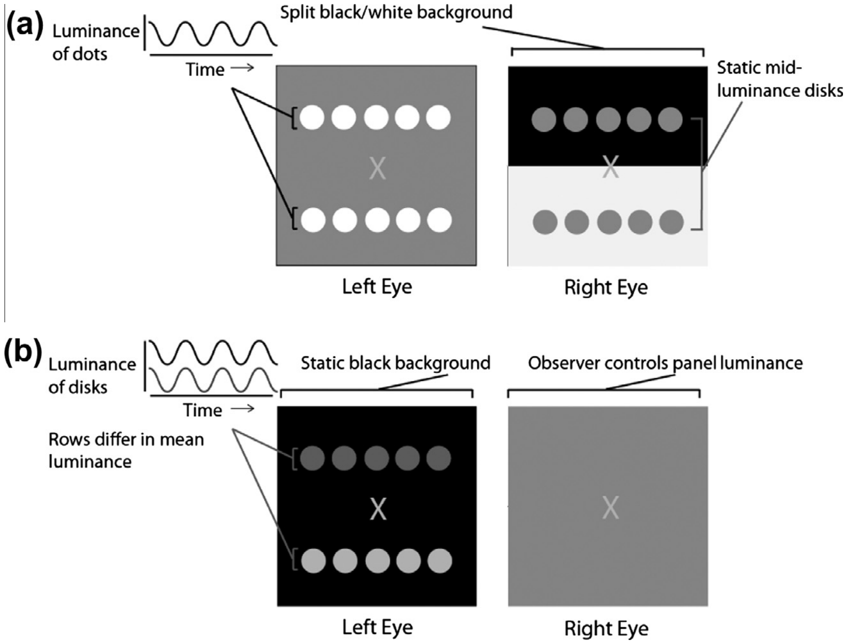

Fig. 7. Two other configurations that demonstrate that the contrast response could be perceived with monocular contrast but not with binocular contrast. Panel (a) is the same as experiment 1 but the static half of the display has gray disks. Panel (b) the mean luminance level of the top row of disks is increased, and the mean luminance level of the bottom row of disks is decreased and the observer controls the luminance of the field without the modulating disks (the right eye in the example above).

background could have shifted the mean level to prevent the appearance of the asynchrony. A background that is a gradient from light to dark allows us to control for this possibility, since there would be a wide range of contrast backgrounds. If binocular contrast affects perception, we would expect to see motion in at least some of the disks.

3.1. Procedure

The conditions of the experiment were identical to Experiment 1, except that instead of a split black/white background, the background for one eye was two gradients that shifted linearly from black to white in opposite directions (see Fig. 5). Observers were asked to indicate whether they perceived motion in the stimulus.

3.2. Results and discussion

As with Experiment 1, observers saw contrast-generated motion in the monocular contrast condition but not in the binocular condition. Fig. 6 plots the proportion of trials where observers reported seeing contrast-generated motion at each modulation amplitude level. The blue squares represent the monocular contrast condition, and the black disks represent the binocular contrast condition. Panel A shows the average of the three observers' results. In the monocular contrast condition, almost all trials were seen as producing motion regardless of modulation amplitude. Panels B–D present individual results; these trends are similar to the average of the data.

As with previous studies (Shapiro & Knight, 2008), the contrast-generated motion was detectable for monocular contrast with even the smallest amount of modulation. The results here show that binocular contrast does not produce a visible contrast asynchrony over the gamut of luminance backgrounds. These results should be expected, since the motion generated is a type of second-order motion. Second-order motion has been reported to occur monocularly but not binocularly (Sperling & Lu, 1998), even though there is a report of binocular second order global motion (Hutchinson et al., 2013).

3.3. Demonstrations that mitigate concerns about light level

The results from Experiments 1 and 2 were unambiguous in showing that the contrast response could be perceived with monocular contrast but not with binocular contrast. Here we present two other configurations that lead to the same conclusion. The demonstration in Fig. 7a is the same as in Experiment 1, but the static half of the display contained gray disks that could be fused with the modulating disk presented to the other eye. In this display, the luminance levels of the disk in both the top and bottom rows were identical in the fused image. In the binocular contrast condition, there was a slight "halo effect" (Bachmann, Breitmeyer, & Öğmen, 2007) surrounding the disks, as the images seen by each eye were different, but the images from the left and right eyes could still be fused. In this condition, observers who viewed the demonstration never reported seeing the asynchrony in the binocular contrast condition.

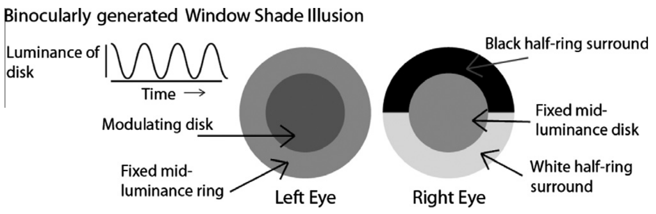

Fig. 8. The stimulus configuration for Experiment 4. In this experiment, one eye is presented with a disk whose luminance modulates sinusoidally in time surrounded by a mid-luminance ring. The other eye is presented with a fixed mid-luminance disk that sits on a split black and white background made of two half-rings. Observers responded to the perceived presence of a "window shading" effect described by Shapiro et al. (2004).

The demonstration in Fig. 7b takes advantage of a stimulus condition mentioned in the discussion of Shapiro et al. (2004). In this condition, the disks have the same temporal phase, but the mean luminance level of the top row of disks is increased, and the mean luminance level of the bottom row of disks is decreased—specifically, the top row of disks had mean of 75 cd/m^2 and modulated between 95 and 55 cd/m^2, and the bottom row disks had a mean of 25 cd/m^2 and modulated sinusoidally between 45 and 5 cd/m^2.

In the monocular condition, the disks in the top and bottom rows appear to modulate in phase when the background is black or white and appear to modulate in antiphase when the background is mid-gray. In the binocular condition, we set the background of the disks to black and allowed observers to adjust the luminance level of the other field. The disks always appeared to modulate in phase with each other regardless of the luminance level—indicating that the luminance of the binocular contrast did not affect the appearance of the asynchrony.

We also note that the perceived amplitude of disk modulation was affected by the luminance of the static field. When the disks are viewed outside of the stereoscope, the modulation depth is affected by the background luminance. Against a black background, the low mean luminance levels have higher perceived modulation depth than the disks with the high mean luminance levels, and vice versa against a white background. In the condition depicted in 7b, the modulation depths were more equal when the static background was near white than when the background was near black. This finding suggests that the binocular contrast can affect the appearance of the disks, but not the asynchronous response.

4. Experiment 3

As stated above, Shapiro, Charles, and Shear-Heyman (2005) showed contrast asynchronies can lead to different sorts of phenomenal experiences: the basic version of the contrast asynchrony produces a separation between luminance and contrast, whereas single field contrast asynchronies such as the window shade illusion produce a shading effect more similar to brightness illusions. Shapiro, Charles, and Shear-Heyman (2005) showed that these two types of experiences behave nearly independently from each other. Here we examine whether the window shade illusion can occur with binocular viewing, thereby indicating another condition that separates these two types of effects. We follow Shapiro, Charles, and Shear-Heyman (2005) and measure the probability of seeing the window shade effects as a function of size of the surrounding ring. Shapiro, Charles, and Shear-Heyman (2005) showed that the window shade illusion becomes stronger as a function of the size of the surrounding ring.

4.1. Stimulus configuration

4.1.1. Apparatus

The apparatus and calibration was the same as in the previous 2 experiments.

The spatial configuration is shown in Fig. 8. One eye was presented with a (6.94 deg) modulating disk on a mid-luminance (50 cd/m^2) gray background ring; the other eye was presented with a fixed mid-luminance disk of the same size as the first disk; the disk was surrounded with a horizontally split black (1 cd/m^2) and white (100 cd/m^2) background ring. The stimuli fused when viewed through the stereoscope to create the percept of a modulating disk on a split black and white background.

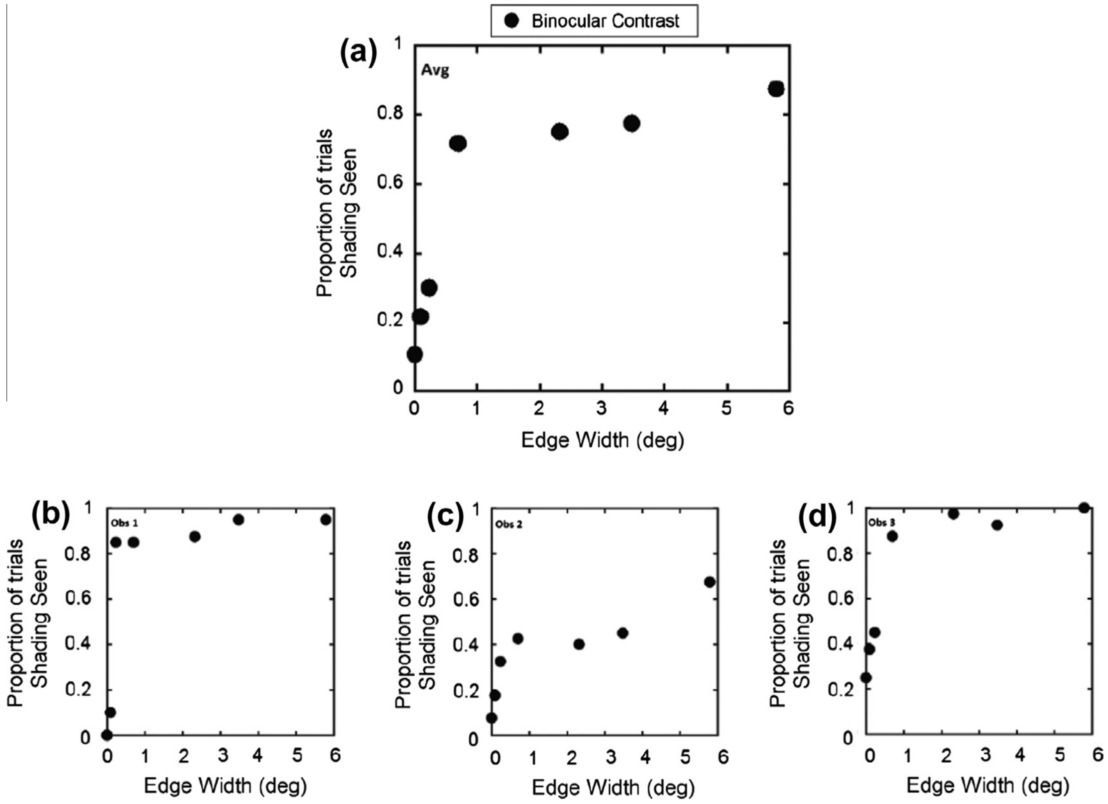

Fig. 9. The probability of seeing shading as edge width of the window shade increases. All conditions were binocular, meaning that while the center stimulus presented to one eye, the edges presented to the other eye. As edge width grew thicker, the probability of the observers perceiving shading rapidly increased before reaching a plateau at around 1 degree of visual angle.

4.1.2. Observers

Participants included three psychology graduate students between the ages of 25 and 30 with normal or corrected-to-normal vision: two were male, and one was female. All three were naïve to the aims of this study and did not participate in the experiments described above.

4.1.3. Procedure

There were two variables manipulated among the conditions: the eye to which the modulating disk presented was randomly chosen for each trial, and the width of the background rings changed in size among seven conditions. Each condition was presented to each participant 20 times, so there were 2 × 7 × 20 trials (280 total). All conditions were "binocular contrast" conditions, meaning the modulating disk and the split backgrounds were never presented simultaneously to the same eye.

Participants responded yes or no to the question "Do you see shading?" Shading is defined by Shapiro et al. (2004) as a "veil" that seems to cross up and down the modulating disk as the contrast changes between the disk and the black/white background ring.

4.1.4. Results and discussion

Fig. 9 plots the probability of seeing shading as a function of the surround field size. Panel A shows the results for the average observer, while panels B–D show the results for the individual observers.

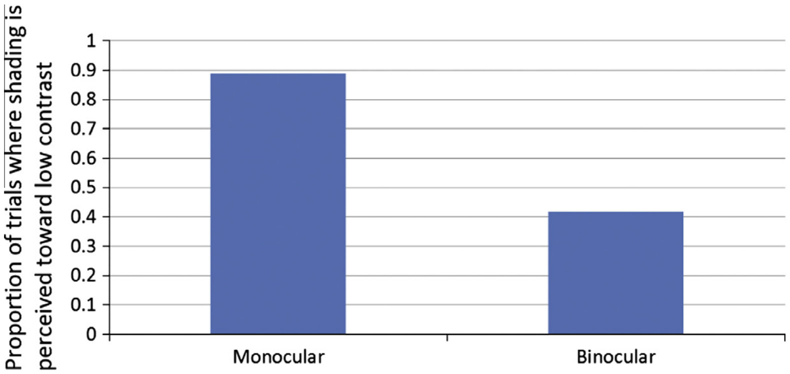

Fig. 10. The results for Experiment 3b show the proportion of trials where observers saw shading toward the low contrast edge during monocular and binocular viewing conditions. Though shading clearly moves toward low contrast in the monocular condition, results for the binocular condition are mixed. Our results from Experiment 3 show that participants see shading in the binocular condition in around 80% of trials, so we do not interpret these results as chance-based due to the forced choice nature of the task.

As with the monocular displays in Shapiro, Charles, and Shear-Heyman (2005), the probability of seeing the shading increased as a function of background size. The individual observers all showed similar results, even though observer 3 had a lower probability of seeing the window shade effect. We found no significant effect of whether the modulating disk was presented to the left or right eye.

The results suggest that unlike the two-disk contrast asynchrony, the window shade illusion occurs in response to binocular contrast. In around 10% of control trials, where the edge thickness was zero, observers still reported seeing the window shade motion even though there was no edge to create such an effect. While 10% is not a large percentage of trials, we note that the response is consistent with informal observations of hysteresis with the stimuli.

5. Experiment 3b

In the monocular version of the window shade illusion, motion heads in the direction of minimal contrast—that is, when the disk is increasing in luminance, the shading heads toward the white half of the ring, and when the disk is decreasing in luminance, the shading moves towards the dark half of the ring (Shapiro, Charles, and Shear-Heyman, 2005). Others have reported effects similar to the window shade illusion. Hsieh, Caplovitz, and Tse (2005) confirm that the effect does not appear to be controlled by attention, while Hock & Nichols (2010) finds that the shading moves in the direction of high contrast. Here we sought to measure whether the direction of shading is the same for binocular and monocular contrast conditions.

5.1. Observers

Participants included three psychology graduate students between the ages of 20 and 30 with normal or corrected-to-normal vision: two were male, and one was female. One was an author of this paper (OJF); the other two were naïve to the aims of this study and did not participate in the previous experiments described above.

5.2. Procedure

The experiment had the same spatial configuration as Experiment 3 but used only a single-diameter surround (13.68° visual angle), and a single modulation depth (0.4). There were 24 trials presented in random order: 12 presented with monocular contrast; 12 with binocular contrast. The observers responded as to whether the shading moved toward the white half ring or the black half ring when the luminance of the center was increasing.

5.3. Results and discussion

Fig. 10 plots the proportion of trials in which shading moves toward low contrast. In the monocular condition, observers saw the shading as moving toward low contrast on about 90% of the trials; in the binocular condition the shading moved towards white on 40% trials. These results are consistent with the phenomenological observation that people report when looking at the window shade illusion in the stereoscope. The monocular condition, therefore, produces motion consistently in one direction, whereas binocularly the direction of motion is ambiguous. The results suggest that monocular contrast sends a consistent signal about motion direction, whereas contrast calculated binocularly does not produce as consistent a signal.

We report here the results for only a single parametric condition (i.e., 0.4 amplitude, fixed diameter of the surround, and fixed contrast of surround). Shapiro, Charles, and Shear-Heyman (2005) parametrically investigated shading in the window shade illusion in non-stereoscopic conditions and always found motion toward minimal contrast. However, we have not investigated the effects of parameter changes on the direction of shading in a binocular contrast configuration. It is perhaps possible that the direction of shading in the binocular contrast can be affected by changing the thickness of the rings or by changing the modulation frequency of the center disk.

6. Discussion

Here we have investigated binocular aspects of displays with asynchronous contrast modulation. We report the following four empirical findings: (1) the perception of the contrast asynchrony is not visible when the two surrounding fields are presented to one eye and the modulating fields are presented to the other; (2) the shading effect in the window shade illusion can be seen binocularly; (3) the probability of seeing shading in the binocular condition increases with the diameter of the surrounding field; and (4) in the monocular contrast condition, observers nearly always report that shading is present and moves towards minimum contrast, whereas in the binocular contrast condition, the direction of shading can be towards either low or high contrast edges. The results are therefore consistent with the idea that the contrast asynchrony differentiates between two types of contrast calculations: the asynchronous appearance represents a contrast calculation that originates in a single eye and cannot be created from combining signals from both eyes; the shading effects correspond to contrast calculations that can originate after a combination of signals from the two eyes even though these contrast responses can be seen monocularly.

Our finding of separate processes for monocular and binocular contrast perception is similar in principle to the finding of Shevell, Holliday, and Whittle (1992), who reported that the surround field creates perceptual assimilation when presented to the opposite eye as the test patch and creates perceptual contrast when presented to the same eye as the test patch. The results lead to the proposal of two different types of contrast responses—one monocular and the other binocular. Such a finding can easily be integrated with Shapiro's quantitative model (2008) (see http://www.journalofvision.org/content/8/1/8, Fig. 5), which proposes two separate types of visual responses: a color contrast response that is fast, rectified, and integrates across color channels, and another color response that is slow and corresponds more directly to the perceptual qualities of color (hue, brightness and saturation). Since the contrast response was relatively fast (the contrast asynchrony is easier to see at 6 Hz than at 1 Hz), Shapiro (2008) suggested that the color contrast pathway originates in the retina; since the perceptual calculation of equiluminant color is slower, Shapiro (2008) suggested that the signal from the color pathway is likely to pass through a cortical filter. The results here are consistent with these suggestions, since shading effects can be seen binocularly and therefore can be constructed after the combination of the signals from the two eyes, whereas the contrast response can be created only monocularly.

There is other evidence for multiple contrast processes involved in color induction: for instance, De Valois et al. (1986) and Rossi and Paradiso (1996) found induction to be slow (i.e., occurring normally at modulation speeds below 6 Hz), whereas Blakeslee and McCourt (2011) found brightness induction to be much faster, prompting them to speculate about a form of induction that does not use a "filling in" process. Also, D'Antona and Shevell (2006) found that while color induction occurs up to 3 Hz (in agreement with De Valois et al., 1986), at higher frequencies the relationship between modulation rate and induction rate is not linear, implying the presence of multiple filters that operate on different temporal scales. Recent work in Shevell's lab has also found that when combinations of high-frequency color modulations are used, the color induction system responds to the beat frequency of the modulation (D'Antona & Shevell, 2009).

As has been suggested previously (Shapiro, 2008), separate contrast pathways may account for the finding that color contrast adaptation occurs at rates much faster than chromatic temporal frequency (Shapiro, Hood, & Mollon, 2003; Webster & Wilson, 2000; Zaidi, Spehar, & Debonet, 1998). Indeed, Zaidi, Spehar, and Debonet (1998) suggested that contrast adaptation corresponds to a retinal mechanism that adjusts to small eye movements, a suggestion that is consistent with the monocular response shown here. It is easy to speculate about the purposes of a cortical filter that leads to a slow temporal response. A binocular contrast response could represent processes that use early contrast signals to construct color appearance. There are many conceivable ways to construct a color signal from a contrast response: for instance, Ioannides, Johnston, and Griffin (2006) suggest a mechanism in which the cortex could use a type of Taylor series expansion to estimate brightness based on contrast and higher-order contrast signals. Such a combination of contrast responses would certainly take time and therefore would not be effective at higher temporal frequencies. There is also the possibility that the shading involves processes further along parts of the visual stream that manage object perception: for instance, recent studies suggest that induction can be affected by object segmentation (D'Antona & Shevell, 2007) and by gestalt organization cues (Schirillo & Shevell, 2000). Presumably, such processing takes place beyond early visual stages, in such areas as the lateral occipital complex (Fang, Kersten, & Murray, 2008; von der Heydt & Peterhans, 1989). We note that Liu and Wandell (2005) found separation between fast and slow color responses, with an area along the ventral occipital lobe (VO) responding to slower chromatic modulation; it is conceivable, therefore, that the slower binocular response reported here represents signals along the slower object pathway.

Regardless of how the cortical contrast arises, binocular contrast seems to lead to a different type of perceptual interpretation than monocular contrast, a result that may be important for interpretations of shading phenomena. Shapiro, Charles, and Shear-Heyman (2005) demonstrated two separate and independent contrast responses for the window shade/rocking disk illusion. The rocking disk illusion occurs from apparent movement at fine edges (this type of motion disappears when the ring is greater than about 10 min of visual angle), whereas the window shade effects occur over large spatial areas and become stronger as the ring increases in thickness, suggesting that the mechanism(s) responsible for producing shading can integrate over a very large (>10 deg) area (again, see detailed animated demonstrations of these stimuli at http://www.journalofvision.org/content/suppl/2011/01/04/5.10.2.DCSupplementaries/5.10.2_supplement.html). Here we have shown that the first type of contrast response originates monocularly and always produces motion towards low contrast, whereas the window shades effects can be created binocularly and seem to be able to produce motion in either a low-contrast or high-contrast direction. Others have found attentional effects on other types of contrast motion (Hsieh & Tse, 2006). Our results suggest the possibility that attention can modify the binocular contrast response in the window shade effects but not the monocular contrast response found in the rocking disk.

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