Visual illusions based on single-field contrast asynchronies

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A single-field contrast asynchrony refers to a stimulus configuration in which there is a single temporally modulated field and multiple sources of contrast information; the sources of contrast information modulate at different temporal phases or at different temporal frequencies. In this paper we show how single-field contrast asynchronies can lead to a wide variety of visual illusions. We investigate, in depth, the window shade/rocking disk configuration, in which a temporally modulated disk is surrounded by a split annulus (i.e., the top half is dark, and the bottom half is light). When the annulus is thick, the disk appears spatially inhomogeneous (shading); when the annulus is thin, the disk appears to rock back and forth (shifting). We measure the proportion of trials that a disk appears to shade or, on separate trials, appears to shift as a function of modulation amplitude, surround thickness, temporal frequency, and disk size. We account for the shading effects by postulating a combination of separate first- and second-order responses and/or a multi-scale spatial filtering process. We account for the shifting effects by examining four elemental motion conditions. For luminance modulation, the direction of the shift follows the same pattern as that produced by the rectified output of an array of spatial center-surround filters applied to the X, t plot. For equiluminant modulation, the direction of the shifts is consistent with a sequence-tracking (or third-order) motion response.

Keywords: illusions, simultaneous contrast, illusory motion, spatial integration, brightness induction, tilt illusions, chromatic motion, contrast asynchronies

Introduction

The information in any visual scene can be expressed in terms of a variety of stimulus characteristics (spatial frequency, luminance, contrast, temporal frequency, chromaticity, etc.). The visual system encodes this information through neural channels, each of which responds to only a small range within a few of these dimensions. One goal of psychophysics is to separate and characterize the response properties of these channels, but this goal is challenging because the signals relayed to the brain from these channels are integrated prior to perception.

This paper examines visual illusions that stem from attempts to construct stimuli that separate the visual response to color/luminance information (first-order response) from the visual response to contrast information (second-order response). The impetus for creating such stimuli came from experiments that showed that chromatic contrast adaptation occurs at rates much faster than the temporal response of chromatic systems (Zaidi, Spehar, & Debonet, 1998; Webster & Wilson, 2000; Shapiro, Hood, & Mollon, 2003). Shapiro et al. (2003) concluded that the system that controls contrast adaptation is not the same as the color pathways that carry the signal that was ultimately detected.

To separate and characterize the first- and second-order color responses, Shapiro & D’Antona (2003); Shapiro et al. (2004a); and Shapiro, D’Antona, Smith, Belano, & Charles (2004b) developed a class of stimuli (termed “contrast asynchronies”) defined by the asynchronous modulation of multiple sources of contrast information. The initial contrast asynchrony consisted of two physically identical disks, one surrounded by a dark annulus and the other by a light annulus. When the luminance levels of both disks are modulated simultaneously, the contrast (relative to the surround) modulates in antiphase, but the luminance levels remain in phase (an interactive version of this stimulus can be seen by clicking on Figure 1).

The two-disk asynchrony indicates that at the level of perception, the visual system is able to represent both luminance and contrast information. For instance, a curious phenomenon associated with the two-disk asynchrony is that at 1 Hz, observers report the paradoxical perception that the disks modulate in antiphase (i.e., with the contrast signal), yet also appear to get light and dark at the same time (i.e., in phase, with the luminance signal). At low temporal frequencies, therefore, the perceptual system can

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separate the response to contrast information from the response to luminance information. At 3 Hz, only the contrast signal could be seen, indicating that the visual response to the contrast information is faster than the visual response to the luminance information.

In addition to presenting the two-disk asynchrony, Shapiro et al. (2004a, 2004b) documented variants in which the antiphase contrast information was integrated within a single disk (see Figure 1, and click on Figure 1 to see interactive demonstration). One variant (which Shapiro et al. 2004a, referred to as a window shade/rocking disk illusion) consists of a disk whose luminance is modulated sinusoidally in time, surrounded by a split annulus, half light and half dark. The contrast at the dark edge is in phase with the luminance modulation, and the contrast at the light edge is in antiphase with the luminance modulation. The appearance of the disk depends upon the thickness of the surrounding annulus. If the surround is thick, a veil of lightness appears to slide back and forth across the disk (like a window shade). If the surround is thin, the disk appears to shift location.

The window shade illusion shows a connection between contrast asynchronies and the effects of the spatial context on lightness/brightness perception. The effects of surrounds on the appearance of a center disk have been studied by generations of artists and scientists (for a historical review, see Kingdom, 1997). There are currently a wide range of theories concerning these types of illusions; for a review of some of these theories, see Adelson (2000); Blakeslee & McCourt (2004); Gilchrist et al. (1999); Kingdom (2003a, 2003b); Purves, Williams, Nundy, & Lotto (2004); Shapley, Caelli, Grossberg, Morgan, & Rentschler (1990). Most (but not all) of these theories recognize the importance of contrast on the appearance of a center field.

The rocking disk illusion (shifting effect) shows a connection between contrast asynchronies and the appearance of motion that arises when shifting between two different contrast levels (see, for instance, reverse phi and four-stroke motion, Anstis & Rogers, 1975, 1986; and the phenomenal phenomena of Gregory & Heard, 1983). The shifting effect may also be related to static tilt illusions such as the café wall illusion, twisted chords, and other recent variations (Kitaoka, Pinna, & Breilstaff, 2004; Pinna & Breilstaff, 2000).

In this paper, we investigate the general principle that a single-field contrast asynchrony with thick borders produces induced shading, whereas one with thin borders produces shifting. We show that the shifting and shading effects depend upon the modulation amplitude and the thickness of the surround. The results are consistent with Shapiro et al.’s (2004a) interpretation that the shading effect produced by a contrast asynchrony results from the interaction of separate responses to the center light (first-order response) and to the contrast between the center and the surround (second-order response), and that the stimulus parameters change the relative weightings of these responses. The first- and second-order responses may result from a multi-scale spatial filtering of the visual image (such as in Blakeslee & McCourt, 2003). We also show that the shading/shifting principle can be used to generate numerous new illusions. The shifting effects produced in these illusions can be explained by examining the output of an array of center/surround filters. Lastly, we note that a sequence-tracking type of motion system can also see motion in this type of stimuli (Derrington, 1985); however, for some contrast-asynchrony configurations, the direction of motion predicted by sequence tracking is the opposite of the direction predicted by the local energy models. Motion for some equiluminant contrast asynchronies is perceived to follow the prediction of the sequence-tracking models.

The effect of modulation amplitude at 1 and 3 Hz

Modulation amplitude and temporal frequency are crucial variables for producing the asynchronous appearance.
of the two-disk contrast asynchrony (Shapiro et al., 2004a). For the two-disk asynchrony, observers were more likely to see antiphase modulation when the modulation amplitude was high and when the modulation was between 3 and 5 Hz. These characteristics were interpreted as a measure of the relative strength of response to the contrast information as compared to the response to the luminance information.

In this section, we examine the parameters for the window shade/rocking disk configuration. Specifically, we ask how the perception of shifting and shading is affected by the parametric manipulation of modulation amplitude. We examine the effects of amplitude for three different surround sizes and two different temporal frequencies.

Apparatus

All studies below were presented on a 21-in. Sony Multiscan G520 monitor using a Cambridge Research VSG 2/3 graphics board. Gamma correction was conducted using a Cambridge Research OptiCal photometer and linearization software. Calibration and gamma correction were checked with a Spectroscan 650 spectroradiometer. The viewing distance was 93 cm.

Observers

There were three observers, between the ages of 20 and 23, who were enrolled in an upper-level Perception Laboratory course at Bucknell University. All three had normal or corrected visual acuity.

Procedure

In the center of the monitor, observers viewed a disk with a split annulus. One half of the annulus had a luminance level of 20 cd/m² (dark) and the other half had a luminance level of 80 cd/m² (light). The center disk had a mean luminance level of 50 cd/m². We examined the effect of modulation amplitude as a function of temporal frequency (1 or 3 Hz), disk area (1° or 8°), and surround thickness (0.22°, 0.89°, and 3.5° for shading; 0.22°, 0.48°, and 1.7° for shifting). The amplitude of modulation varied between 0 and 30 cd/m². We express amplitude on a scale from 0.0 (no modulation) to 1.0 (modulation amplitude of 30 cd/m²).

Observers were asked one of two questions: Was the disk shading in appearance (yes/no)? Or (on separate trials) did the disk appear to move (yes/no)? The relevant features of modulation always consist of both luminance and contrast components. It is impossible to change one of these values without changing the other. The stimulus, therefore, does not lend itself to a Type A experiment (Brindley, 1960) or to a forced-choice type of experiment. We therefore settled upon measuring observers’ reports of the appearance of the stimulus, bearing in mind that this leaves the interpretation of the results open to questions of observer bias.

Observers ran the experiment in sessions with a fixed stimulus configuration (i.e., fixed temporal frequency, disk area, and surround size). The order of the stimulus presentation was determined prior to the start of the experiment. The observer viewed 10 presentations of the stimulus at each of the eight amplitude values. After each presentation, the observer pressed arrows on the keyboard to indicate whether the disk appeared to be shading or (on a separate session) whether the disk appeared to be shifting. The observer ran two sessions for each stimulus configuration (i.e., twenty presentations of each stimulus configuration for shading, and twenty presentations for shifting).

Results and discussion

Figure 2 shows the proportion of trials perceived as shading as a function of modulation amplitude. The data represent the average for the three observers. The data from individual observers have been posted with this manuscript and can be seen from the following link. The rows present the data measured at different temporal frequencies (1 and 3 Hz), and the columns present different disk diameters. In each panel, the symbols indicate the thickness of the surround (black circles, thin; green triangles, thick; and blue squares, thickest). For a 1°/1 Hz disk (upper left), the two thicker-surround conditions produce a standard monotonically increasing psychometric function that reaches a value of 1 at a magnitude of 0.3. The thin surround condition (black circles) produces a nonmonotonic function. At a modulation amplitude of 0.2, the disk was most frequently perceived as shading; at higher amplitudes, the disk was less frequently perceived as shading. Similar patterns are shown for an 8°/1 Hz disk (upper right panel) and a 1°/3 Hz disk (lower left panel).

In the 8°/3-Hz condition (lower right panel), the shading effect is seen less frequently—indeed, two of the observers seldom reported seeing shading in this condition. The upper temporal limit for shading depends upon the diameter of the disk. This suggests that shading depends upon a neural “filling-in” process: The large area and faster central modulation do not give enough time for the contrast induction to spread across the field.

The nonmonotonic relationship between the appearance of shading and the amplitude of modulation (Figure 2) parallels visual-evoked potential (VEP) results of Crognale, Switkes, & Adams (1997). In their study, Crognale et al. measured VEP response to gratings modulating in counter phase at 4 Hz and found a nonmonotonic relationship between the amplitude of the VEP 2nd harmonic and the contrast of the gratings. They stated that the nonmonotonic relationship was believed to be the result of
multiple generators that had different temporal frequencies but “had little or no consequence for the perception of contrast per se.” Here we suggest the possibility that a counter-phase modulating grating produces a visual response to both first- and second-order information. It is therefore conceivable that the nonmonotonic relationship found by Crognale et al. is related to the phenomena shown here.

Lastly, it is worth noting that although all three observers showed the nonmonotonic functions, this result depends on a subjective task. When shown a window shade illusion with large modulation and thin surrounds, half of a class of twelve students reported seeing shading, and the other half reported seeing the disk as uniform (with thick surrounds, they all reported seeing shading). This suggests that in a larger population there will be variability either due to response biases or to differences in the relative strength of the processes that respond to the first- and second-order information. Individual differences on such a task would be consistent with Shapiro et al. (2004b) and with other studies that show variability in contrast response (e.g., Fraser & Wilcox, 1979; see also Backus & Oruç, 2004).

Figure 3 shows results for the apparent shifting of position as a function of modulation amplitude. The symbols and panels are the same as in Figure 2. The apparent shifting consistently increased with the modulation amplitude. Shifting occurred most frequently with the thinnest surrounds and least frequently with the thicker surrounds.

The curves were steeper for 8° disks than for 1° disks (i.e., the amplitude at which the observer saw the rocking 50% of the time is smaller for the 8° disks than for the 1° disks). The probable reason for this is that the edges for the 8° disks are in the visual periphery. Other illusions that show motion with contrast (e.g., Pinna & Brelstaff, 2000) are often more noticeable in the periphery. It is likely that such effects have to do with the larger receptive fields in the periphery. Lastly, the results for the 1- and 3-Hz conditions are similar even for 8° disks. This suggests that a neural filling-in process like the one used to explain the results for induced shading is not necessary for shifting.

The results are consistent with the interpretation that the relative strength of the processes that respond to first- and second-order information changes with the stimulus configuration. This interpretation assumes that (1) the response to first-order information creates the appearance of a uniform disk, and the response to second-order information leads to the appearance of shading and to the appearance of shifting; (2) the strength of the response to the second-order information that leads to shading increases as the thickness of the surround increases; and (3) the first-order response as a function of modulation amplitude increases faster than the second-order response in this stimulus. Thus, when the surrounds are thin and amplitude is large, the response to first-order information is greater than the response to second-order information. As the surrounds become larger, the magnitude of the second-order response is more on par with the magnitude of the first-order response.

The surround thickness for producing shifting and shading

In this section, we ask how thick the annulus has to be before the disk stops looking as if it is shifting position and
starts looking as if it is shading. We measure psychometric functions for the appearance of shading or (on separate trials) shifting as a function of surround size. We measure the effect for different-sized centers and for two different modulation amplitudes.

Observers

There were 10 observers: 5 ran the 0.3 amplitude condition and the other 5 ran the 1.0 amplitude condition. All observers had normal acuity or were optically corrected. One additional observer reported that he never perceived shifting and was excluded from the study.

Procedure

The basic task was the same as the previous section. Observers were asked whether the disk appeared to shade or shift position. The method of constant stimuli was used to measure psychometric curves (proportion of “yes” responses versus annulus thickness). These curves were measured for six different disk diameters (0.25°, 0.5°, 1°, 2°, 4°, and 8°) and for two modulation amplitudes (0.3 and 1.0).

In each session, observers saw 10 presentations of six disk diameters and eight surround thicknesses. There were four sessions: In two sessions, the observer was asked whether the disk appeared to shade, and in the other two, the observer was asked if the disk appeared to shift (thus, there were twenty presentations of each diameter and surround combination). The observers in the 1.0 modulation condition ran four sessions for both horizontal-split and vertical-split surrounds. The 0.3 modulation condition was run as a follow-up to the 1.0 modulation experiment; observers in the 0.3 modulation condition saw only the horizontal-split surrounds.

Results and discussion

Figure 4 shows typical sets of psychometric functions for a single observer in the condition in which the amplitude equals 1.0. The upper panel shows the proportion of shading versus the annular thickness. The lower panel shows the proportion of time the observer saw the disk

Figure 3. The proportion of trials perceived as shifting versus the modulation amplitude. Each panel is for a different combination of temporal frequency and disk diameter. The symbols indicate surround diameter: black circles, thin (0.22°); green triangles, thick (0.44°); and blue squares, thickest (1.7°). The data are averaged over three observers; data for individuals can be viewed here.
The thresholds for both shifting and shading tracked each other closely (shading: threshold = 0.18 × log(diameter) + 0.14; shifting: threshold = 0.14 × log(diameter) + 0.21). This means that shading started and shifting stopped at approximately the same surround thickness. For a modulation amplitude of 1.0, the threshold curve for shading rose much more steeply than for shifting (shading: threshold = 0.46 × log(diameter) + 0.35; shifting: threshold = 0.11 × log(diameter) + 0.23). As a result, for a substantial range of surround thicknesses, the disk appeared stationary and uniform: The disk did not shade or shift for the area between the lower shifting threshold and the upper shading threshold. The range increased with the disk diameter. These shifting measurements correspond roughly to measurements of ganglion cell receptive field centers. The receptive field centers for M and P ganglion cells (physiologically defined) increase from a radius of about 10 min at 4° peripherally to about 20 min at 10° in the periphery (Derrington & Lennie, 1984; Sun & Lee, 2004).

These results indicate that for most observers the uniform appearance created by high luminance modulation levels can be countered by increasing the size of the surround. Such results are consistent with the interpretation put forth in Shapiro et al. (2004a) and in the previous section; the appearance of the disk depends upon the relative weighting of the response to the luminance and contrast information.

Lastly, the data from the individual observers can be seen in the following link. The results for most observers followed the trends in the averaged data. However, two observers (one in the 1.0 condition, and one in 0.3 condition) had shading thresholds pinned at a thickness of 0.11° for almost all disk areas. These observers, therefore, almost always reported seeing shading whenever a split annulus was present. A debriefing with these observers after the experiment indicated that they understood the task, and they were giving an accurate report of their perceptions; their reports indicate the possibility of individual differences in the contrast response.

**Shifting and shading can occur simultaneously**

The results from the previous sections make it unlikely that the processes responsible for shifting and shading are yoked. To see that shifting and shading can be perceived simultaneously (click on the “add gap” button in Figure 1); this will place a thin gray gap between the surround field and the modulating disk. When the surround is thick, the center disk appears to shift within the confines of the surround and still can be perceived as shading (although the strength of the perceived shading is less than when the gap is not there).

**Figure 5** shows the threshold curves for the shifting and shading conditions. The curves are the average of five observers. Panel A shows the thresholds for an amplitude of 0.3, and panel B shows thresholds for an amplitude of 1.0. The circles indicate lower thresholds for shading (i.e., shading is reported for thicknesses above these values). The colored symbols in panel B represent horizontal (open red symbols)- and vertical (open blue symbols)-split surrounds. In panel A, the task was measured only on horizontal-split surrounds.

For both modulation amplitudes, the mean threshold thickness for shading and for shifting rose linearly as a function of log disk diameter. For a modulation amplitude of 0.3, the thresholds for both shifting and shading tracked each other closely (shading: threshold = 0.18 × log(diameter) + 0.14; shifting: threshold = 0.14 × log(diameter) + 0.21). This means that shading started and shifting stopped at approximately the same surround thickness. For a modulation amplitude of 1.0, the threshold curve for shading rose much more steeply than for shifting (shading: threshold = 0.46 × log(diameter) + 0.35; shifting: threshold = 0.11 × log(diameter) + 0.23). As a result, for a substantial range of surround thicknesses, the disk appeared stationary and uniform: The disk did not shade or shift for the area between the lower shifting threshold and the upper shading threshold. The range increased with the disk diameter. These shifting measurements correspond roughly to measurements of ganglion cell receptive field centers. The receptive field centers for M and P ganglion cells (physiologically defined) increase from a radius of about 10 min at 4° peripherally to about 20 min at 10° in the periphery (Derrington & Lennie, 1984; Sun & Lee, 2004).

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Orientation and the interpretation of the rocking disk illusion

In this section, we document that when the surround in the rocking disk illusion has a horizontal split, motion appears to originate from two focal points (the disk rocks up and down), and when the surround has a vertical split, motion appears to originate from a single focal point (the disk pivots back and forth).

Procedure

There were 16 naïve observers, each of whom ran in individual sessions. We used a physical disk (a CD) to illustrate what we meant by “rock” (i.e., perceived motion that originated from the intersection of the light and dark segments of the annular surround) and by “pivot” (i.e., perceived motion that was tied to a single focal point). The set of stimuli contained disks of 0.25°, 0.5°, 1°, 2°, 4°, or 8° diameter; each of these had a thin annular surround (0.05°) that was split vertically (i.e., the intersections of the surrounds occurred at 90° and 270°) or horizontally (the intersections occurred at 0° and 180°). The order of presentation was generated by the MatLab randomization routine. Observers viewed each presentation for 5 s. The observers were asked whether the disk appeared to move; if they responded yes, they were asked whether the disk appeared to pivot or rock.

Results and discussion

The results are shown in Table 1. Almost all of the observers reported that the disk appeared to shift position (12–15 out of 16, depending on the diameter of the disk). One observer reported never seeing motion. For most disk sizes, most observers who saw motion in the vertical-split condition reported that the disk appeared to pivot from a single focal point (like a pendulum), and most observers who saw motion in the horizontal-split condition reported that the disk appeared to shift from two focal points.

The stimulus in the horizontal-split condition was frequently described as appearing to flip out of the plane of the image (in one observer’s words, “A movement like that of a butterfly valve”). Those who perceived a three-dimensional aspect in the stimulus reported that in the dark phase, the disk appeared tilted away from the observer, and in the light phase, it tilted toward the observer. The description of the stimulus as a “butterfly valve” suggests that the horizontal-split stimulus can be interpreted in a manner analogous to a 3-D object illuminated with a single source originating from above.

Variations of contrast-asynchrony illusions

In this section, we show that the same basic principle for creating the window shade/rocking disk illusion can generate a wide variety of new shading/shifting illusions. Many of these were mentioned as possibilities in Shapiro et al. (2004a, 2004b), but here we show active demonstrations. We also show that, as with the window shade/rocking disk illusion, a thin gap produces the appearance of shifting and shading simultaneously.

Tilt and ramp illusions

An interactive movie that shows that the tilt and ramp illusions can be seen by clicking on Figure 6. The illusions consist of a spatially uniform rectangular patch of light whose luminance level modulates in time. The buttons in the interactive movie control the placement of luminance ramps (i.e., a rectangular patch that varies from light to dark). When the ramps are adjacent to the modulating patch, the physical contrast between the patch and the dark portion of the ramp modulates out of phase with the physical contrast near the light portion of the ramp. The buttons on the bottom change the thickness of the ramp or place a gap between the ramp and the modulating field (these alterations create conditions that are analogous to the surround thickness and gap in the window.
and Zaidi & Sachtler (1991). When the ramps are thin, tilt back and forth out of the plane of the image. Some observers report that the edges appear to change local to the edge. The induced lightness moves up and down the edge of the modulating field in opposite directions. When the ramps are thin, the center field appears down the mid-luminance gap creates the impression of a field that is both changing luminance and shifting at the edges. So, just as in the case of the window shade/rocking disk illusion, the impressions of shifting and shading can occur simultaneously.

Figure 6d shows an equiluminant version of the ramp illusion. The extent to which the lights are truly equiluminant, of course, depends on the projection system and individual observer; nonetheless, the effect is fairly robust and should be seen in most displays. Unlike in the achromatic conditions, the motion appears to be confined within the ramps. Also, when the modulating field is reddish, it tilts toward the reddish end of the ramps, and when the field is greenish, it tilts toward the greenish end of the ramps. In the Discussion section, we show that this type of motion may be the result of a sequence-tracking type of process. Under some stimulus conditions, the same type of motion pattern can also be created with achromatic lights.

**Gauge asynchrony (with and without a perimeter) and the step illusion**

An interactive movie that shows the gauge asynchrony can be seen by clicking on Figure 7a. The gauge asynchrony is the inverse of the tilt and ramp illusions: A modulating field surrounds a fixed rectangular luminance ramp. The contrast modulation at the top of the ramp is in antiphase compared to the contrast modulation at the bottom of the ramp. As the background changes from dark to light, the illusion grows out of discussions concerning Vernier acuity with Barry Lee at SUNY College of Optometry.

Figure 6a presents two ramps, both with the same orientation (in this case, dark on bottom, light on top). When the ramps are thick (“thick flanks button”), the rectangular field appears to be of nonuniform lightness; an illusory divider at the point of 0 contrast appears to shift up and down the ramp, giving the impression of a sliding change in lightness. The effect, therefore, is a temporal version of other ramp induction effects introduced by Kingdom & Moulden (1991), Kingdom (2003a, 2003b), and Zaidi & Sachtler (1991). When the ramps are thin, some observers report that the edges appear to change thickness, whereas others report that the field appears to tilt back and forth out of the plane of the image.

In Figure 6b, the orientation of the left ramp is inverted so that the luminance goes from light on bottom to dark on top. When the ramps are thick, the induced signal does not carry across the modulating field, but instead it stays local to the edge. The induced lightness moves up and down the edge of the modulating field in opposite directions. When the ramps are thin, the center field appears to tilt left and right in phase with the modulation.

In Figure 6c, a single ramp is located on the right side of the modulating field. When the ramp is thick, a small change in lightness occurs along the edge, but the rest of the modulating field appears uniform. When the ramp is thin, one side of the field appears to tilt left and right, whereas the other side appears stationary. This indicates that shifting effects can occur on a single edge and do not require asynchronous contrast signals across the whole modulating field. However, the addition of modulating contrast signals on other borders can make the whole field appear to shift position.

In Figures 6a, b, and c, a button allows for the insertion of a mid-luminance gap between the ramp and the modulating field. When the ramps are thick, the mid-luminance gap creates the impression of a field that is both changing luminance and shifting at the edges. So, just as in the case of the window shade/rocking disk illusion, the impressions of shifting and shading can occur simultaneously.

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to light, the ramp appears to be divided wherever the contrast is 0 (i.e., the point at which the luminance level of the background matches the luminance of the ramp). The perceptual effect is that of a gliding scale in which a divider slides up and down the ramp. The contrast on either side of the divider is clearly signed and therefore can be best considered in terms of Whittle's (1994b) construct of brightness contrast. Future experiments will examine how the gradations of lightness are dispersed along the scale—i.e., whether the gradations are determined by an "anchoring" type rule (Gilchrist et al., 1999) or by a histogram equalization principle (MacLeod, 2003; Zaidi et al., 1998).

The effect is referred to as a gauge asynchrony because the divider can be used as a gauge that indicates the luminance level of the background light (Shapiro et al., 2005). For instance, if the ramp and the modulating background go from dark to bright (i.e., the full range of available luminance), then the divider will appear to slide up and down the whole length of the ramp. If the background modulation consists of turning on and off a red phosphor, then the divider will appear to slide up and down only over a small portion of the length of the ramp. If the background modulates between two lights that have the same luminance, then the divider will appear to remain fixed at a particular level on the luminance ramp.

In the interactive movie, the "add perimeter" button creates a thin mid-luminance perimeter around the center ramp. As with the rocking disk and tilt illusions, modulation of the background makes the stationary field appear to expand and contract, although here the effect is not as dramatic. When the perimeter is shown by itself, the lightness of the field appears to change, but the field does not appear to expand or contract. The graded perimeter, when shown without the gauge, creates an effect similar to the original gauge asynchrony.

Figure 7b shows that the gauge asynchrony effect can also be produced with discrete lines instead of a continuous ramp. This format may prove to be useful for gauge photometry. The appearance of the shifting edge is weaker than with a continuous ramp.

**Pulsing: center modulation**

In Figure 8a, the luminance of the center fields of a square, a hexagon, and a diamond is modulated next to stationary borders. The "same sides" button places dark borders on one half of each polygon and light borders on the other half. The polygons appear to shift up and down, just as in the rocking disk illusion. When the modulation is in the light phase, the polygons appear to move in the direction of the dark edges, and when the modulation is in the dark phase, the polygons appear to move in the direction of the light edges. The "opposite sides" button alternates dark and light sides. In this condition, the polygons appear to contort.

The pulsing effects can be eliminated by extending the borders outward (with the "square with long" button and "hexagon with long" button); the effect of the extended borders is analogous to the effect of a thick annulus in the window shade/rocking disk illusion. In the case of the square, extended borders create the impression of square sitting in the middle of the intersection of a dark and light rectangle. The modulation creates the impression of transparency and scission. In the light phase, the white rectangle appears in front; in the dark phase, the dark rectangle appears in front. At intermediate phases, the square appears transparent. Curiously, the scission and transparency effects do not occur for the hexagon; the impression is that of a hexagonal field in the center of rectangular patches.

These effects are similar to a variety of effects in the literature (Gregory & Heard, 1983; Anstis & Rogers, 1975). For comparison, we have included an interactive version of Gregory & Heard's (1983) configuration in Figure 8b. Their effect differs in that they modulated the surrounding field. Similar but unpublished effects have been developed by Anthony Norcia ("the gaping maw" illusion, personal communication), and Baingo Pinna (personal communication). Howard Hock's has laboratory developed similar effects concurrently and independently (see Nicholas & Hock, 2004). These effects were also noted in Shapiro & D’Antona (2003), Shapiro et al. (2004a, 2004b), and Shapiro, Shear-Heyman, Milanak, Leaver, & Charles (2004c). In many respects, as Gregory and Heard have pointed out, these effects are dynamic versions of Helmholtz’s (1866/1962) illumination phenomena, which show static bright objects against static dark backgrounds to be larger than the inverse. The apparent paradox (for our illusions, the dark centers against dark edges move inwards) can be explained by local motion energy, as will be shown in the Discussion section.
Pulsing: edge modulation

Illusions similar to those in the previous sections can be created by modulating thin edges around a stationary center. In Figure 9, as the edges around a stationary square modulate, the square appears to contort. The buttons change the relative phase of edge modulation as well as the luminance level of the square. The square appears to expand and contract when the edges modulate in phase with each other. The square appears to contort when opposite edges modulate in phase with each other (click on button labeled “out of phase Modulation 1”). The square appears to shift position when the phase of modulation of contiguous edges is shifted by half a cycle (click on button labeled “out of phase Modulation 2”). The last condition is similar to a button in a graphical user interface (GUI) design.

The rule governing the position shifts appears to be the opposite of the rule for center modulation (previous section): When the center field is dark, an edge in the dark phase will appear to move outwards and in the light phase will move inwards. When the center field is light, an edge in the dark phase will appear to move inwards and in the light phase will appear to move outwards.

Generating complex illusions from simple asynchronous elements

The basic elements from the previous demonstrations can be combined to create many novel and very dramatic illusions. Here we show three such configurations. Lucy in the Sky (Figure 10a) is composed of modulating diamonds. The diamonds are configured either as a chain or in a loop. The phase of the luminance modulation of each diamond is offset relative to the others. The buttons control the relative orientation of the edges. The apparent movement of the diamonds makes it hard to believe that the edges are stationary.

The honeycomb configuration (Figure 10b) consists of a number of hexagons. The buttons control the luminance level of the edges and the relative phase of the luminance modulations. The honeycomb appears to distort and wobble in a manner that makes the surface appear to be elastic.

The house of cards effect (Figure 10c) consists of stacked squares. The buttons change the luminance level of the edges. When the edges of a square are both white and black, the square appears to distort or shift position. Combinations of distorted and shifting squares can be used to give the impression that a number of the squares are moving together. The result is an effect that appears like a dynamic café wall illusion.

The illusions created from multiple elements appear to be more dramatic than those composed of single elements. This suggests, not surprisingly, that contrast-asynchrony illusions can be subject to long-range Gestalt-like processes.

Discussion

Contrast asynchronies arise whenever a stimulus configuration contains contrast signals that differ in temporal phase (Shapiro et al., 2004a, 2004b). This paper examined contrast asynchronies that arise within a single visual patch. As a rule, thin borders create the appearance of shifting, and thick borders create the appearance of shading (or brightness spreading). We have shown that this rule can be applied to a variety of stimulus conditions to generate a wide range of new visual illusions.

At low modulation levels, the threshold thicknesses for shading are approximately the same as the threshold thicknesses for the elimination of shifting. The similar thresholds might suggest a common etiology for the two perceptual responses—for instance, when the borders are smaller than a ganglion cell receptive-field center, the edge appears to move, but when the borders are larger than the center, the edge appears to shade. However, for high modulation levels there is a range of disk areas and
surround thicknesses that most observers perceive to neither shift nor shade. We have also demonstrated that shifting and shading can be perceived at the same time; therefore, the mechanisms underlying these effects do not appear to be yoked.

In the sections below, we discuss the mechanisms underlying shifting and shading as if these two aspects of contrast asynchronies are independent of each other.

Shading effects

Contextual effects on the center modulation have been the source of numerous theories concerning the nature of context on visual appearance. The results here and in Shapiro et al. (2004a) show that observers can perceive both a first-order response originating in the center modulation and a second-order response resulting from the contrast modulation. The two responses remain separate late enough to be distinguished from each other perceptually (as in the two-disk contrast asynchrony). It is likely that the separation results from some form of multi-scale spatial filtering of the visual scene, such as that described in the model presented by Blakeslee & McCourt (1999, 2003, 2004). Blakeslee and McCourt’s model involves multiple levels of the oriented differences of Gaussians (ODOG) that combine through a normalized output channel. Their account has been successful at describing a wide range of static lightness illusions.

However, a dynamic multi-scale model has a number of additional factors with which it must contend. For instance, to account for the appearance of the two-field asynchrony, a dynamic model would have to produce multiple output channels that could be identified perceptually. Some of these channels would presumably respond in phase with center modulation; others would respond in antiphase with the contrast, depending on the size of the surround.

Furthermore, although most of the examples shown so far seem amenable to the suggestion that shading is simply a low spatial frequency response, there are other examples that indicate that the second-order effects are quite sensitive to thin edges. Figure 11a shows the two-field asynchrony as rectangular bars. In the interactive demonstration, the levers control thin bars that can extend from the top and bottom of the rectangles. The fields initially appear to modulate in antiphase. When very thin edges are added at the top and bottom of the modulating fields, the fields appear to modulate in phase. Conversely, if the modulating fields are placed in a White’s effect configuration (i.e., as if the modulating fields were placed on light and dark bars), the fields appear to modulate in phase, and the addition of thin edges produces the appearance of antiphase modulation (Shapiro et al., 2004c). Thus, any model that describes the asynchrony as the response to a low spatial frequency filter also has to account for the apparent effect of high-spatial frequency edges.

The effect of thin edges can also be shown in a single-field contrast asynchrony (see Figure 11b, the barbell illusion). This illustration shows a modulating bar placed between two static squares, one light and one dark, separated by a gray field. If the bar extends into the squares, the bar appears to shade. The effect may at first appear to be the result of a low-frequency filter because the shading extends over a large range of the modulating field. However, if there is a thin gap between the modulating bar and the squares, the shading effects stops, again indicating the possible effect of high-spatial frequency edges.

These effects should not be considered an argument against a dynamic multi-scale model, but rather a cautionary note concerning the range of effects that a complete model will need to describe. It is possible, for instance, that a small gap will decrease the response of the low spatial frequency filter in such a way as to decrease the appearance of shading. Or perhaps there is an active interaction between the response from high spatial frequency filters and response from low spatial frequency filters that would allow for the sharpening of edges. We are currently constructing a model that will allow for the testing of such hypotheses.

Figure 11. Two illusions that show the effect of edges on contrast asynchronies. (A) The asynchronous appearance of the two-field asynchrony is suppressed when thin edges are added to the top and bottom of the surrounding field. Conversely, the asynchronous appearance is not present when modulation occurs in a White’s effect configuration. The asynchrony reappears when thin edges are added. (B) The Barbell illusion. The appearance of shading occurs if a modulating bar extends into two static squares (one white and one black). The shading disappears if the bar is reduced so that there is a thin gap between the bar and the squares. Click on figures to see interactive demonstrations.
It is also possible that there really are separate processes for first- and second-order information. Lights, after all, can be described by their contrast relative to their surround (a second-order response) and by their relative brightness levels (a first-order response). For example, consider the four disks in Figure 12, which represent two frames from the two-disk contrast asynchrony. The disks can be described by their relative brightness (the disks on the bottom are both dark, and the disks on the top are both light) or by the relative apparent contrast (the top-left and bottom-right are high contrast disk/surround pairs, and the top-right and bottom-left are low contrast disk/surround pairs). Indeed, if one considers this division seriously, then the paradoxical perception produced by the two-field asynchrony (i.e., that they modulate in antiphasic but get light and dark at the same time) should not be at all surprising.

It is possible that the division between high/low contrast and high/low lightness (such as that shown in Figure 12) is the end product of some multi-scale spatial filtering of the stimulus. One way that this could arise is that the first-order appearance could be constructed at later stages of visual processing. Such a system would be efficient (Why send two signals down the optic nerve when it may be possible to send only one? See Barlow, 1965) and consistent with the slow response to the information in the center relative to the contrast information (Shapiro et al., 2004a). This type of system can explain why there is a reduction in shading for large disks (8°) with 3 Hz modulation (Figure 2) and other large shading effects such as the “watercolor” illusion (Pinna, Brelstaff, & Spillman, 2001). Another possibility is that the separation of contrast and lightness arises from the mechanisms like the plenoptic structures of Adelson & Bergen (1991). Viewed from this perspective, contrast asynchronies would represent processes that respond to light changes over time versus processes that respond to the spatial derivative over time. Such mechanisms have been suggested previously in the literature (see Brown, 1965).

A late combination of separate first- and second-order responses could be a process for creating a signed contrast signal, such as that suggested by Whittle’s brightness contrast (1994a, 1994b) and by Gilroy & Hock (2004) who used a two-field contrast asynchrony to investigate apparent motion across disks. The physiological evidence for such a division is sparse; however, there does appear to be a subset of cortical cells that may respond directly to first-order information (Kinoshita & Komatsu, 2001). In addition, a division between first- and second-order responses may be related to different divisions between contributory elements proposed by other studies: for example, boundary contour versus feature contour (Grossberg & Todorović, 1988; Rudd & Zemach, 2004); retinal contrast versus cyclopean mechanism (Shevell, Holliday, & Whittle, 1992); and even contrast versus assimilation (Hong & Shevell, 2004; Jameson & Hurvich, 1964; Reid & Shapley, 1988).

A separation between first- and second-order responses may prove useful for models of lightness constancy. Whittle & Challand (1969; see Brown, 2003) have argued in favor of the two types of constancy: one for illumination changes that affect both the background and the foreground object (contrast remains constant) and another that arises when an object moves in front of two different backgrounds (luminance remains constant). The lack of attention to the second type of constancy has been harshly criticized (Gilchrist, 1994; Gilchrist et al., 1999; Gilchrist & Economou, 2003). This type of constancy seems to directly correspond to a second-order response.

Shifting effects

As mentioned above, several authors have shown position shifts that arise with changes in luminance (Anstis & Rogers, 1975; Gregory & Heard, 1983; Mather, 1984). The illusions presented here have several features not shown in the previous studies: (1) The position shifts arise with the modulation of only an edge, or of the field on one side of a stationary edge. (2) The position shifts can occur across a static mid-luminance gap interposed between the modulating field and a static bright or dark patch. (3) The orientation (i.e., vertical or horizontal split) of the surround creates different perceptual interpretations. (4) The position shifts for equiluminant ramp effects move in the direction of similar colored borders, whereas the shifts for most achromatic conditions are in the opposite direction. (5) The effects can be reduced to elemental conditions that can be combined to generate a variety of illusory configurations. As noted above, effects similar to Point 1 have been shown in unpublished demonstrations (Norcia, personal communication; Pinna,
personal communication) or developed concurrently and independently while addressing different questions (Nicholas & Hock, 2004). Most of these effects were also noted by Shapiro & D’Antona (2003) and Shapiro et al. (2004a, 2004c).

To analyze the shifting effects presented here, we reduce the illusions to four novel elemental conditions shown in Figure 13a. The conditions consist of modulation of the edge adjacent to a stationary light or dark center (Figure 13a, top two panels) and modulation of the center adjacent to a stationary light or dark edge (Figure 13a, bottom two panels). The red ring on the left edge of each figure indicates the portion that we will model. The animated movie presents conditions where the edges are thin and conditions where the edges are thick. No motion is perceived when the edges are thick. A convenient way to represent the stimulus is with an \((X, t)\) plot (thin edges, Figure 13b; thick edges, Figure 13). Each \((X, t)\) plot corresponds to the red circled region in the top panels. The \(y\)-axis is time \((t = 0\) is at the top), and the \(x\)-axis shows the spatial position of the display. The red arrows indicate the direction of apparent motion for the thin-edge conditions.

The direction of motion produced by edge modulation seems at odds with the direction of motion produced by center modulation. When the edges are modulating, they appear to move away from the similar shadings of the center (i.e., a dark edge moves outward when modulation is in the dark phase, and it moves inward when modulation is in the light phase; a light edge moves inward when modulation is in the dark phase, and it moves outward when modulation is in the light phase). When the center is modulating, the edges appear to move toward similar shadings in the center (i.e., a dark edge moves inward when modulation is in the dark phase, and it moves outward when modulation is in the light phase; a light edge moves outward when modulation is in the dark phase, and it moves inward when modulation is in the light phase).

Reichardt detectors

One possible explanation is that the apparent shift in position is the result of motion energy at the modulation boundaries. Such motion energy would be seen in Reichardt detectors. Reichardt detectors compare the output of two receptors that are cross correlated over time. To identify motion in a left-to-right direction, the luminance level at one spatial location and at time \(t\), \(f(X, t)\), is multiplied by the luminance level at a different spatial location and with a brief time delay, \(f(X + \Delta_x, t + \Delta_t)\). Right-to-left motion is calculated by a signal at \(f(X + \Delta_x, t)\) multiplied by a signal at \(f(X, t + \Delta_t)\). The difference of the responses, \(M\), indicates the direction of motion:

\[
M = f(X, t)f(X + \Delta_x, t + \Delta_t) - f(X + \Delta_x, t)f(X, t + \Delta_t).
\]

If \(M\) is positive, the detector indicates right-to-left motion, and if \(M\) is negative, the detector indicates left-to-right motion.
Reichardt detectors predict motion where there are orientation changes in an $X,t$ plot (Adelson & Bergen, 1985). As one can see in Figure 13, there is some directional energy whenever the luminance of the modulating edge coincides with the static portion of the static field. This motion energy is in the direction of the red arrows. In Figure 14, the top four panels show the output when the edges are thin, and the bottom four panels show the output when the edges are thick. Light pixels indicate motion to the right; dark pixels indicate motion to the left; and gray pixels indicate no motion. Reichardt detectors predict motion correctly in the thin-edge conditions but also predict identical motion in the thick-edge conditions, where no motion is perceived.

We can therefore reject Reichardt detectors (with unfiltered input) as an explanation for luminance edge motion.

**Position shift predicted by an array of center-surround filters**

One explanation for why we see position shifts for thin edges and not for thick edges is that spatial position is determined from an array of spatially band-passed filters. This explanation is consistent with the observations that the critical thickness for apparent shifting corresponds roughly to measurements of ganglion cell receptive field centers (Derrington & Lennie, 1984; Sun & Lee, 2004) and that there is a close parallel between retinal M-cell response to slowly changing stimuli and psychophysical Vernier performance (Rüttiger, Lee, & Sun, 2002). Filtering the input creates a mechanism for “spatial smoothing,” as suggested by Anstis & Rogers (1975, 1986) and others (Lu & Sperling, 1999; Mastebroek & Zaatman, 1988) to account for reverse phi and four-stroke motion, and as suggested by Morgan & Moulden (1986) to account for static tilt illusions.

To show the effects of this approach on the four elemental conditions of Figure 12, we filtered each horizontal line of the $(X,t)$ plots with an array of symmetric center-surround spatial filters. The filters were of length $3N$ and of the form:

$$f(i,N) = [-i/2N...-i/2Ni/N...i/N-i/2N...-i/2N],$$

where $i$ is either $-1$ or $1$. When $i = 1$, the filter is on-center; when $i = -1$, the filter is off-center. So, for instance,

$$f(1,2) = [-1/4-1/41/21/2-1/4-1/4].$$

Figure 15 shows the output of an array of center-surround filters [$f(1,8)$, the center is twice the size of the edges]. Each value of $X$ represents a filter centered at a different location. Bright pixels indicate filters with positive outputs; and dark pixels indicate filters with negative outputs. Shifts in the position of bright and dark pixels over time indicate a shift in the location of high and low response filters and, presumably, the perceived location of the edge boundary.

For the thin-edge conditions, the location of the maximum and minimum luminance values shifts over time. All plots show shifts in the perceived direction. However, for the modulating center conditions, the direction of the shift depends upon the spatial properties of an upstream system. If the system examines peak responses, the border moves in one direction. If the system examines the troughs, the border moves in the other direction. There is the additional problem that all of these surround-minus-center filters are presumably accompanied by the opposite polarity center-surround filters in the visual system [i.e., the opposite-valued filter, $f(-1,8)$, produces plots with the opposite polarity]. The directional components from one system would cancel out the motion from the other.
These problems can be overcome by rectifying the output of the spatial filters (Figure 16). The brighter the pixel, the greater the response from the underlying filter, with gray equal to 0. In the thin-edge conditions, the movement contour is defined either by the bright bands or by the location of the local zero output in the filter array. The direction of the contour follows the direction of perceived motion. In the thick-surround condition, the contours do not shift the relative position. The observed position shifts are consistent with a process that determines edge location based on the rectified output of an array of center-surround filters. The thicknesses for which the shifting effects occurs (10–20 min of arc) suggest that these filters could be the retinal ganglion cells.

Combining the elemental conditions to make more complex displays

Figure 17 illustrates how an array of center-surround filters can be used to predict position shifts in more complex displays. The top panel shows a single frame from the tilt asynchrony. The bottom two panels show the $(X,t)$ plots from the top and bottom edges of the modulating rectangle. These $(X,t)$ plots show position shifts in opposite directions, thus producing a tilting appearance. Because these $(X,t)$ plots are the same as the $(X,t)$ plots for the modulating center conditions in Figure 12, any model that predicts position shifts for these conditions will also predict position shifts in the same direction for the other illusions.

Curiously, the direction of the shifts indicated by the local edges of the ramp is different from the direction of motion predicted by a sequence-tracking (or global) system.
Conclusion

The visual illusions shown in this paper were all generated with the same underlying principle (i.e., stimuli in which the contrast signals modulate out of phase with each other). Thick-edge contrast asynchronies create the appearance of shading; thin-edge contrast asynchronies create the appearance of shifting. Explanations of shading effects seem to require either a combination of the visual response to contrast and luminance information or separate analysis by multi-scale spatial filters. Shifting effects can be accounted for by examining the response of an array of center-surround filters.

The threshold thickness for apparent shifting corresponds roughly to measurements of ganglion cell receptive field centers. The receptive field centers for M and P ganglion cells (physiologically defined) increase from a radius of about 10 min at 4° peripherally to about 20 min at 10° in the periphery (Derrington & Lennie, 1984; Sun & Lee, 2004). The results are therefore consistent with Sun, Ruttiger, & Lee’s (2004) suggestion that positional sensitivity is the result of a sophisticated cortical interpretation of the output of the ganglion cell array.

The information contained in an array of center-surround cells may correctly predict the presence and direction of shifting but cannot explain the interpretation of the stimulus. Table 1 shows that observers reported that motion within a vertical-split surround appeared to pivot from a single focal point, and motion within a horizontal-split surround appeared to bounce up and down in the plane of the image or to flip out of the plane of the image (in one observer’s words, “A movement like that of a butterfly valve”).

We have no firm explanation for why there should be differences between the appearances of the horizontal- and vertical-split conditions. However, the description of the stimulus as a “butterfly valve” does suggest that the horizontal-split stimulus can be interpreted in a manner analogous to a 3-D object illuminated with a single source originating from above. This aspect of the effect suggests explanations based on inferences about illumination and reflection (Helmholtz, 1866/1962) or on theories that assume that two-dimensional lightness illusions are related to the observer’s learned understanding of the three-dimensional world (for instance, Purves et al., 2004).

Our proposal should not be taken as an argument that higher-order inferences are not involved in lightness/brightness perception, but rather that the input into higher-order processes should be considered in terms of a filtered visual image, not the image per se. (After all, why should early filtering have such a clear effect on motion but no effect on lightness/brightness?)

Our interpretations are, in principle, consistent with Kingdom’s (2003a, 2003b) proposal regarding levels of brightness perception and with Blakeslee & McCourt’s (2003) multi-scale filtering model. However, based on the evidence here and in Shapiro et al. (2004a), we emphasize that the visual system can respond simultaneously to luminance and contrast information. The perceptual response must therefore represent more than the summed responses of the filters’ output. We also would not be surprised if under some conditions the network of filters acted as if there were neural filling-in, and if the network turned out not to be passive, but worked to maximize the informational content in the display (Barlow & Foldiak, 1989; MacLeod, 2003; Zaidi & Shapiro, 1993).

The contrast-asynchrony principle(s) can be used to generate an infinite number of illusions. We have concentrated our investigations on luminance and luminance contrast; however, analogous illusions can be created on a
variety of stimulus dimensions (orientation, color, spatial frequency, contrast-contrast induction). Indeed, contrast asynchronies are possible in principle for any stimulus dimension along which contrast effects can be observed; for example, faces (Webster, Kaping, Mizokami, & Duhamel, 2004) or blur (Webster, Georgeson, & Webster, 2002). Most of these variations have not yet been explored.

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