

Induced contrast asynchronies

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We document a new type of perceptual effect in which asynchronous contrast signals are presented simultaneously with synchronous luminance signals. The template for the basic effect consists of two physically identical disks (.75-deg diameter, 40 cd/m²), one surrounded by a dark annulus (1.5 deg, 20 cd/m²) and the other by a light annulus (1.5 deg, 60 cd/m²). The center disks are modulated in time, with a maximum luminance of 55 cd/m² and a minimum luminance of 25 cd/m². With this stimulus configuration, the luminance signals of the disks modulate in phase with each other while the contrast signals relative to the surrounds modulate in anti-phase. Observers can track the contrast and luminance signals when the luminance is modulated at 1 Hz but perceive primarily the contrast signal at 2-6 Hz. We show that the asynchrony can be perceived with a thin annular surround, that the appearance of the asynchrony is dependent on the modulation amplitude, and that a decrease in the relative strength of the asynchrony at 1 Hz corresponds to the band-pass shape of the temporal contrast sensitivity function in the presence of light and dark edges. We also introduce variations of the induced contrast asynchrony principle in which a single modulated disk is surrounded by a half-light and half-dark split annulus; we refer to these configurations as the window-shade and rocking-disk illusions.

Keywords: simultaneous contrast, brightness induction, illusion, temporal frequency, winking effect, window-shade illusion, rocking-disk illusion

Introduction

Simultaneous contrast phenomena demonstrate that the appearance of a patch of light depends not only on the light itself, but also on the context in which the light is presented (Chevreul, 1839/1854/1967; Helmholtz, 1866/1962; Hering, 1905/1964). A typical example of simultaneous contrast involves two white disks, one surrounded with a dark annulus and the other surrounded with a light annulus. The disk surrounded with a light annulus appears darker than the disk surrounded by the dark annulus.

The examination of simultaneous contrast phenomena has a long history (see Kingdom, 1997). One school of thought associated with Hering (1905/1964) argues that simultaneous contrast phenomena occurs because the primary signal (i.e., the visual response to the center light) is laterally inhibited by a context signal (i.e., a signal that takes into account the difference between the center and surround lights). Numerous studies have shown the limitations of lateral inhibition for explaining simultaneous contrast (Adelson, 1993; Gilchrist, 1977; Shevell, 1986), which

suggests that brightness is also mediated by a range of mid-level or high-level processes that control the weighting or the manner in which the contextual information influences the primary signal (Adelson, 2000). For instance, simultaneous contrast can at least be partially explained by scission (Anderson, 2003), anchoring (Gilchrist et al., 1999), influences of edges and junctions (Todorovic, 1997; Zaidi, Spehar, & Shy, 1997), the addition of contrast gain controls (Singer & D'Zmura, 1995), separate mechanisms for "cyclopean" representation (Shevell, Holliday, & Whittle, 1992), three-dimensional effects (Logvinenko & Kane, 2003), Gestaltian groupings (Agostini & Proffitt, 1993; Wolff, 1933), or some combination of these factors (Bonato, Cataliotti, Manente, & Delnero, 2003).

Regardless of the nature of the study, the visual system is generally assumed to compute lightness following the combination of primary and context signals. Here we present a new type of visual effect—the *induced contrast asynchrony*—that demonstrates that the primary signals can be separated perceptually from the context signals. The prin-

ciple underlying the effect is robust and can be generalized to a wide variety of stimulus configurations.

An example of the basic effect can be seen in the interactive movie in Figure 1. The movie shows two disks whose luminance levels are modulating in time. One disk is surrounded by a dark annulus and the other by a light annulus. The initial impression is that the disks are alternating out of phase with each other. However, when there is no surround, it is clear that the luminance levels of the two disks are always identical. A closer examination of the stimulus with the mask removed demonstrates the central paradox of the effect: Even though the disks appear to be modulating in anti-phase, with attention one can discern that the disks are becoming lighter and darker at the same time.



Figure 1. Click on the figure to view interactive movies that demonstrate the induced asynchrony.

Figure 2 shows the principle underlying the induced contrast asynchrony. In the illustration, the light annulus has a luminance level of 60 cd/m^2 , the dark annulus has a luminance level of 20 cd/m^2 , and the center lights have a mean level of 40 cd/m^2 . The luminance level of the center disks is modulated at 1 Hz with an amplitude of 15 cd/m^2 . The lower left panel plots the luminance levels of the disks versus time. Because the luminance levels are identical, the two lines plot on top of each other. The lower right panel plots the Michelson contrast of the disks relative to the surround. The contrast signals are modulated in anti-phase. When the luminance modulation is in the light phase, the disk with the light surround has a low-contrast value, and the disk with the dark surround has a high-contrast value; when the luminance modulation is in the dark phase, the opposite occurs.

The effect arises, in part, because of the conflict between the luminance and contrast signals. If our perception tracks the luminance level of the disks, then the disks should appear to be modulating in phase; if our perception tracks the contrast signal, which arises at the edge, the disks should appear to be alternating. Because at low frequencies both aspects can be perceived, the effect indicates that at a relatively late stage of visual processing, the signals that

originate from the center of a patch of light can be separated perceptually from signals that originate at the edges.

We write here to document some aspects of this visual effect. At 1 Hz, observers are able to respond to both the in-phase and out-of-phase components of the stimulus; at higher frequencies (2-6 Hz), observers report perceiving primarily the contrast signal; above that level, the disks are modulating too fast to perceive phase differences. We show that the effect can occur with a thin ($.05 \text{ deg}$) ring surround as well as with a thick surround ($.75 \text{ deg}$). The drop in the anti-phase appearance at 1 Hz appears to be related to the band-pass shape of the temporal contrast sensitivity function in the presence of dark and light edges.

We further demonstrate that the underlying principle (i.e., in-phase luminance modulation and anti-phase contrast modulation) can be applied to a single patch of light. We examine a modulation disk with a thick annular surround that is half dark and half light. Under this condition, a veil appears to cross back and forth over the disk. When the surround is thin, the disk appears to pivot or shift position. We refer to these effects as the *window-shade* and *rocking-disk illusions*.

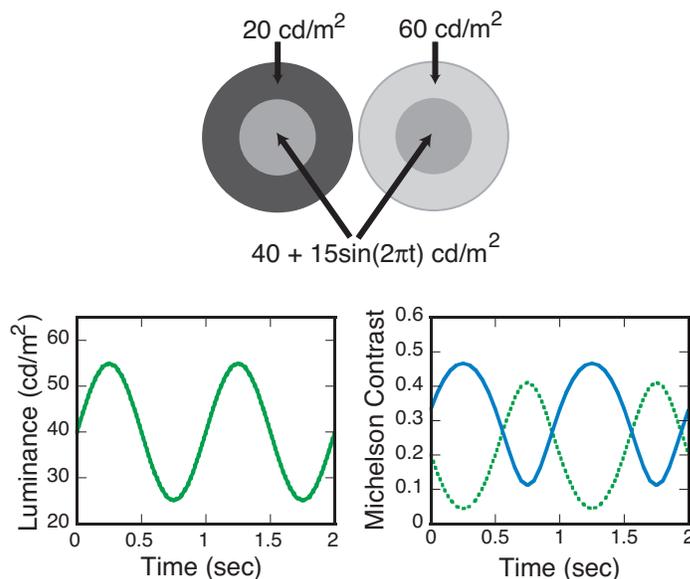


Figure 2. The top panel shows the spatial and temporal characteristics for a typical demonstration of the effect. The lower left panel shows the luminance levels of the center disks versus time. The curves plot on top of each other because the disks have identical luminance levels. The lower right panel shows Michelson contrast $(L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$ for the center disks relative to the surround (green line for the left circle and blue line for the right circle). The contrast signals are modulated in anti-phase.

Experiment 1: Observers can respond to both the luminance and contrast signals

Upon viewing the stimulus shown in Figure 1, observers consistently report that they initially see the disks modulating in anti-phase, but with attention, they also perceive that the lightness is modulating in phase. The paradoxical aspect of the effect can be made evident when showing the demonstration to a small audience ($n \geq 2$). When presented with the display, the members of the audience report that the disks are modulating out of phase with each other. To demonstrate that the lightness is modulating in phase, we asked half of the audience to attend to the disk with the dark annular surround and asked the other half to attend to the disk with the light surround. We then asked each group to respond (i.e., tap or say "light") when the disk appears to be at maximum lightness; the groups respond in synchrony, demonstrating that the disks are getting light and dark at the same time even though the perception of anti-phase modulation persists.

To document the contrast/luminance dichotomy in the laboratory, we had observers view each circle/surround and tap a response button to indicate when the circle reached a perceived maximum lightness or the circle reached a perceived maximum contrast. When asked to attend to the lightness of the disk, observers tap in phase, and when asked to attend to the contrast (i.e., the maximum salience) of the disks, observers tap in anti-phase.

Methods

Apparatus

All three of the studies below were presented on a 21" Sony multiscan G520 monitor using a Cambridge Research VSG 2/4 graphics board. Gamma correction was conducted using 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

The observers were color-normal (FM-100, Ishihara plate test), 20-year-old college students, one male and one female.

Procedure

The spatial configuration is similar to Figure 2. The center disks had diameters of 0.75 deg, and the surround annuli a diameter of 1.5 deg. The centers were modulated at 1 Hz. Each modulation was presented for 20 s. The observers first viewed the dark surround circle and tapped the return key on a computer keyboard to indicate when they perceived the signal to be at maximum lightness. After a short break, the same process was repeated, but the observers tapped the keyboard to indicate when they perceived

the circle to have maximum contrast. The procedure for perceived maximum lightness and contrast was repeated for the light surround circle. The time of the onset of each tap was measured with the timer on the VSG board.

Results and conclusion

The results for two observers are shown in Figure 3. The blue line indicates that the circle had a light surround, and the green line that the circle had a dark surround. The x-axis indicates the time of the observers' tap, and the y-axis is of arbitrary height. The stimulus lasted for 20 s; we show only the final 10 s of each session.

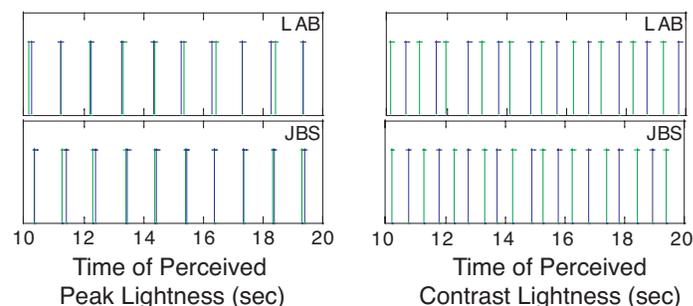


Figure 3. Observers viewed each circle in isolation and tapped a keyboard to indicate the perceived peak in lightness (left panels) or the perceived peak in contrast (right panels). The x-axis indicates the time since the onset of the stimulus. The stimulus lasted for 20 s; only the final 10 s of each session is shown. Each mark indicates the time of the onset of the observer's tap. The green lines indicate taps corresponding to a circle with a light surround, and the blue lines indicate taps corresponding to a circle with a dark surround. The vertical height of the plot is arbitrary.

The left panels of Figure 3 show the time of the taps when the observer attended to the perceived maximum lightness. The taps occurred at nearly the same time for both disks (i.e., synchronous with the luminance signal). The right panels show the time of the taps when the observer attended to the perceived maximum contrast. These taps occurred at the anti-phase peaks (i.e., synchronous with the contrast signal). Therefore, the observers could track both the luminance and contrast signals.

Experiment 2: The effect of temporal frequency and modulation amplitude

Experiment 1 measured an observer's ability to track the luminance and the contrast signals at 1 Hz. The task could not be performed at higher frequencies (2-6 Hz) because the shift in luminance becomes increasingly difficult to follow. In this experiment, we examine how temporal frequency affects the appearance of the contrast asynchrony for a fixed contrast modulation.

Because the stimulus always contains both contrast and luminance information, it is difficult to isolate either of the signals. We therefore measured observers' reports concerning whether the stimulus appeared to be modulating in phase or out of phase.

Observers

The two observers were color-normal (FM-100, Ishihara plate test), 20-year-old college students. Each of these observers had previously run over 40 hr on tasks related to the induced contrast asynchrony.

Procedure

The spatial configuration was the same as in Figure 1. The independent variable was the frequency of modulation of the center disks (1, 2, 3, 4, 5, 6, 8, 12, 15, and 20 Hz). Each presentation lasted for 3 s. In a single session, all 10 frequencies were presented in random order, 8 times each. The observer responded as to whether the disks appeared to be modulating out of phase (yes or no), or the observer rated the perceptual magnitude of the anti-phase signal (1 to 5: 5 when the disks appeared entirely out of phase; 1 when the disks appeared either entirely in phase or were modulating too fast to see them as out of phase).

Results and conclusion

The left panel of Figure 4 shows the results from two observers on the yes/no procedure. The proportion of time the observers said that the center lights are out of phase is plotted versus the temporal frequency of modulation. Both observers responded "yes" most frequently when the stimulus was between 3 and 5 Hz. Above 6 Hz, the observers seldom saw the stimulus in anti-phase. The lights at these frequencies were clearly flickering, but the observers could not tell the phase relationship. There was no distinction between the separate color mechanisms for the frequency of maximum asynchronous response.

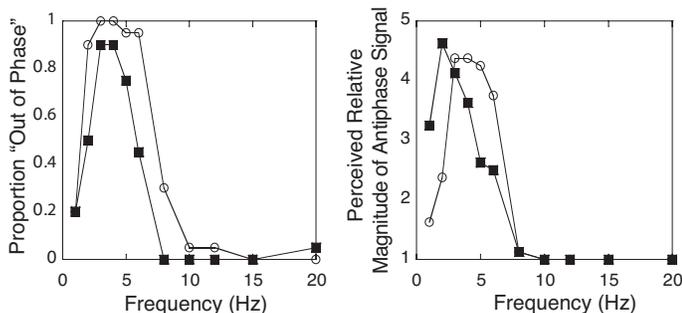


Figure 4. Left panel. The proportion of times that the disks appeared to be modulating in anti-phase versus the frequency of modulation for two different observers. Squares are observer JBS, and circles are observer LAB. Right panel. Subjects rated the relative magnitude of the out-of-phase signal relative to the in-phase signal at different temporal frequencies (1 indicates no perceived anti-phase modulation, and 5 indicates only anti-phase modulation).

Because we were surprised to find the drop at 1 and 2 Hz, we reran the experiment with observers making rating judgments. These results are plotted in the right panel of Figure 4. The pattern is similar to those of the yes-no task. We can conclude that under these conditions, with these experienced observers, the maximum frequency is about 6 Hz, and there appears to be a drop in the magnitude of the asynchrony at low frequencies.

Experiment 3: Temporal range of the asynchrony on naïve observers

The observers in the previous study had been working with the stimulus on a daily basis for 2 months, and we were concerned that the drop in out-of-phase response was the result of this prolonged exposure. We were also concerned that the out-of-phase response might be the result of the limited duration of the test. If there was a delay for the contrast signal to "kick in," then the 1-Hz signal would be less likely to be perceived in anti-phase.

In this section, we reran the test on naïve observers, and extended the duration of the presentations. We also varied the thickness of the annulus and the diameter of the disk. We reasoned that the drop in the anti-phase appearance at 1 Hz might be more likely if the contrast signal was weaker, and we assumed that the strength of the contrast signal would be lessened in relation to the luminance signal if the surrounds were thinner or the center disks were larger.

Observers

Eight senior undergraduates and two master's level students served as observers. All had normal acuity or were optically corrected. A few of them had seen demonstrations of the effect, but they had not been part of an experiment with the two-disk stimulus. One additional observer began the experiment, but did not complete the task because she could not see the anti-phase signal consistently.

Procedure

To make sure that observers understood the distinction between an in-phase signal and an anti-phase signal, we showed them the effect with modulations at 1 and at 3 Hz. The demonstration procedure was similar to the procedure discussed in the "Introduction." After the demonstration, the observers were told that they would see a series of presentations with the disks modulating at different frequencies. They were instructed to press the left arrow key if the disk appeared primarily to be modulating in anti-phase and the right arrow key if the disk appeared primarily to be modulating in phase or if the disks were modulating too fast to tell the phase relationship.

The procedure was the same as in the previous section, except that the duration of each trial was 5 s, and the observers ran each session only once. There were four condi-

tions: two diameters for the central disk, .75 deg and 2 deg, and two annular thicknesses, .05 deg or .75 deg.

Results and conclusion

The averages of the response rates are shown in Figure 5. The axes are the same as in Figure 3 (i.e., proportion of trials perceived as out of phase versus the frequency of the test). The filled squares show the results for the thick annuli (.75 deg), and the open circles show the results for the thin annuli (.05 deg). The results for small diameter disks are shown on the upper left panel, and those for large diameter disks are shown on the upper right. The bars indicate 1 SE.

The pattern of the data in some ways resembles the pattern of the data from the previous experiment. On the high frequency end, all conditions showed a cut off between 6 and 8 Hz, at which point the disks were flickering too fast to determine the phase relationships. The cut off was slightly higher in the thin surround conditions.

The drop at 1 Hz was least noticeable in the condition with a small diameter disk with the thick surround annuli (squares in Figure 5, panel A). In this condition, only three of the observers produced a substantial drop at 1 Hz, thus the average of the naïve observers' responses in the condition most similar to that used in the previous experiment did not become lower at 1 Hz.

This drop at 1 Hz is seen most strongly in the thin surround and large disk conditions (paired t tests all had $p < .1$). However, even with the large diameter disk and thin surrounds, three of the observers produced curves that had a shape that was more low pass than band pass. The drop in the anti-phase signal at 1 Hz is found in most observers, but not in all observers. As will be shown below, the range in observer responses may due to individual differences in contrast sensitivity.

We think it unlikely that the drop is due to a fixed delay time. The drop in out-of-phase response is still present with longer duration presentation. We also showed that the

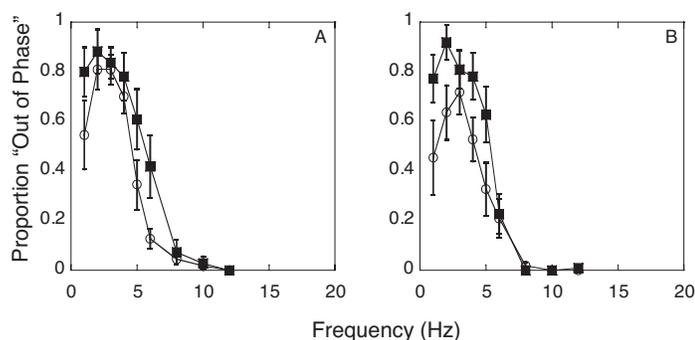


Figure 5. A and B. The average from nine observers showing the proportion of trials in which modulation appeared in anti-phase plotted as a function of frequency of modulation. The filled symbols are for annuli of width .75 deg, and the open symbols for annuli of width .05 deg (i.e., a thin ring around the outside of the disk). A shows small disks (.75-deg diameter), and B shows large disks (2-deg diameter). The error bars depict 1 SE.

drop in out-of-phase response at 1 Hz is more pronounced with the thin surround than with the thick annular surround. This would imply that if there was a time delay for the perception of anti-phase signal, then the delay would depend on the extent of the contrast edge.

Lastly, we note that thin annular surrounds are capable of producing the asynchrony. This indicates that the contrast signal arises primarily at the edge.

Experiment 4: The effect of modulation amplitude

In the previous experiments, the modulation amplitude remained fixed. Here we measure the appearance of the asynchrony as a function of modulation depth. The center disks are modulated at 1, 3, and 6 Hz to see if the relationship described in the previous sections holds at a variety of modulation depths.

Observers

The three observers were color-normal 20-year-old college students, two of whom were experienced observers and one naïve. All three did not know the aims of the experiment.

Procedure

The procedures were similar to those in Experiment 3. The mean luminance levels of the center disks were always 40 cd/m² and the surrounds had luminance levels of 20 and 60 cd/m². The disks were .75 deg, and the surround was 1.5 deg in diameter.

Observers viewed disks with modulation amplitudes of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20 cd/m² and frequencies of 1, 3, and 6 Hz. In each session observers viewed 10 presentations of each luminance and frequency combination (240 trials total). The presentation order was randomized by the MatLab routine. Observers ran two sessions separated by a short break. The task was the same as in Experiment 3: indicate whether the disks appeared primarily to be modulating in anti-phase.

Results and conclusion

The results for three observers are shown in Figure 6. The proportion of trials reported as out of phase is plotted as a function of modulation amplitude. As the amplitude of modulation increased, so did the proportion of trials that appeared out of phase.

As would be expected from the temporal sensitivity measurements and from Experiments 2 and 3, observers reported that the modulation appeared out of phase more often at 3 Hz than at 1 Hz. One observer was able to reliably detect the 6-Hz modulation. For this observer, the out-of-phase response increased with modulation level. For the other two observers, the 6-Hz modulation was too fast to tell the difference in the phase relationship. The third observer showed a monotonic relationship for the 3-Hz modulation but not for the 1-Hz modulation.

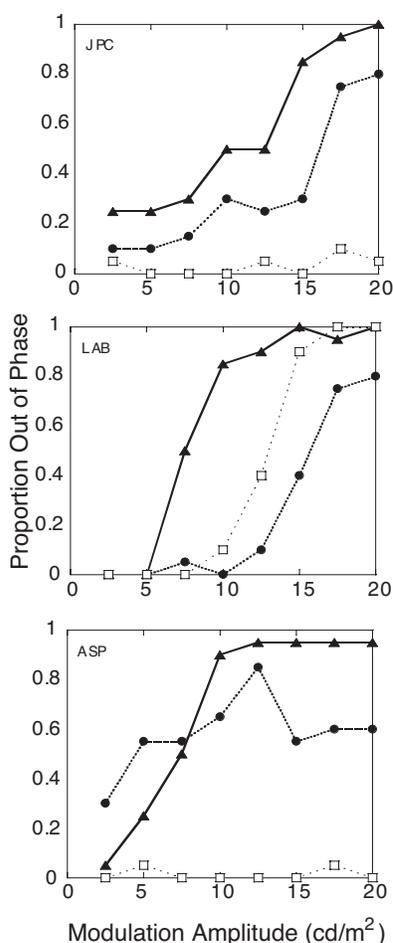


Figure 6. The proportion of out-of-phase response versus the amplitude of modulation. Each panel shows the results for a different observer. There were three temporal frequencies: 1 Hz (filled circles), 3 Hz (filled triangles), and 6 Hz (open squares).

Experiment 5: Temporal contrast sensitivity with luminance edges

Experiment 4 showed that modulation amplitude clearly has an effect on the perception of the anti-phase signal. This finding may account for the decrease in anti-phase appearance at 1 Hz: if observers were less sensitive to 1 Hz than to 3 Hz, they would be less likely to see the anti-phase signal at 1 Hz.

A drop in the relative magnitude of an anti-phase signal at 1 Hz is consistent with the effects of contrast edges on temporal sensitivity (Anderson & Vingrys 2001; Harvey 1970; Keesey 1970; Kelly 1969, 1976; Spehar & Zaidi 1997;). The temporal contrast sensitivity function is low pass against an equiluminant background and is band pass against light and dark backgrounds.

In this section, we measured the effect of edges on the temporal contrast sensitivity function with stimuli similar to those in Experiments 1-4. We then examined the effect

of modulation amplitude on the proportion of trials in which the asynchrony is perceived. A drop in contrast sensitivity should create a similar shift in the perceived asynchrony at all modulation amplitudes.

Observers

The two observers were color-normal college students, one of whom did not know the aims of the experiment.

Procedure

We measured temporal sensitivity in a four-alternative forced-choice task. A 1.5-deg diameter circle was presented in the center of 40 cd/m² achromatic background. The circle was quartered by two oblique lines. The lines and the perimeter of the disk had a width of .2 deg.

On each trial, one of the quadrants was modulated in luminance for 1 s. The frequency of the modulation was either 1, 2, 3, 4, 5, 6, 8, 10, 12, or 15 Hz, so as to evenly divide into the 120-Hz frame rate. The observer's task was to identify which quadrant contained the flickering test light. A 2-up-1-down staircase controlled the amplitude of modulation, and terminated at the end of 10 reversals. Threshold was the mean of the last 6 reversals. Each staircase was run 4 times. As depicted in Figure 7, there were three different surround conditions. The disk and the oblique lines were 20 cd/m², 40 cd/m², or 60 cd/m². In the 40-cd/m² condition, the circle was tinted with a faint equiluminant hue (3x threshold in the +LM cardinal direction) in order to assist with spatial localization.

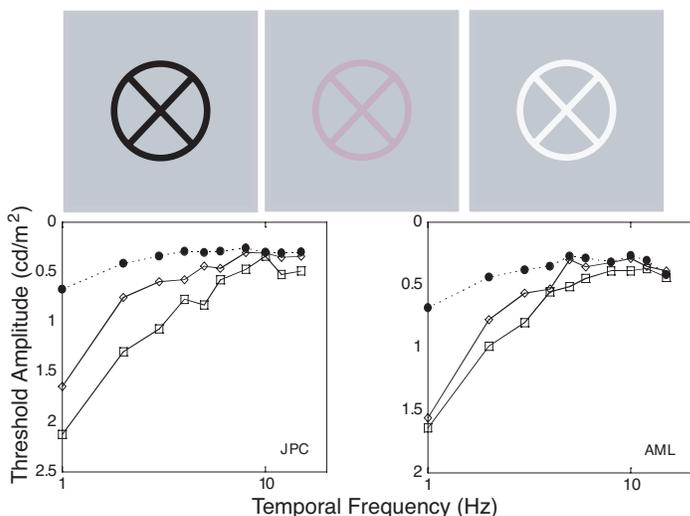


Figure 7. Top. The three stimulus arrangements for measuring temporal sensitivity. The observer had to identify the quadrant that contained a modulating light. There were three surround conditions, a dark surround (left), a light surround (right), and a faint equiluminant surround. Lower figures. Temporal modulation sensitivity for two observers: dark surround (open squares), light surround (open diamonds), and the faint equiluminant surround condition (filled circles).

The observer initially adapted to the circle/ background combination for 30 s. There was a 2-s interstimulus interval after the presentation of each trial. In each session, staircases were run for all temporal frequencies in random order. In each session, a single circle condition was run; these conditions were selected in ABCCBA order.

Results and conclusion

The results for two observers are shown in the bottom panels of Figure 1. Threshold amplitude is plotted versus temporal frequency. The equiluminant surround condition is represented by filled circles and the contrast edges by the open symbols. Consistent with the previous studies, the introduction of light and dark contrast edges reduces sensitivity for low frequency modulation. From 8-15 Hz, the three conditions produce nearly equal modulation sensitivity.

A contrast edge, therefore, creates a drop in modulation sensitivity at 1 Hz; this effect disappears as the frequency increases. Some have argued that such differences indicate that temporal sensitivity functions are the product of multiple channels, one of which is an inhibitory high spatial-frequency mechanism responding to the contrast edge (Anderson & Vingrys, 2001; Kelly 1976;). Alternatively, Spehar and Zaidi (1997) have argued that the shape of the temporal sensitivity curve is determined by the response to temporal changes at the edge of the test or to the center of the test (whichever is more sensitive).

Another interpretation is that detection is determined by the contrast signal in all three surround conditions. The contrast signal in the equiluminant condition is modulated at twice the frequency of the contrast signal in the dark and light conditions. If the data in Figure 7 are re-plotted as a function of contrast frequency (i.e., doubling the frequency of the equiluminant condition on the x -axis), then the thresholds in the equiluminant condition equal those in the light surround condition.

Regardless of the interpretation, the results show that the contrast signals are relatively weaker at 1 Hz than at 3-6 Hz when the modulation field is surrounded by a light or dark field. It is therefore possible that the shape of the perceived asynchrony versus temporal curves (shown in Experiments 2 and 3) corresponds to the visual response to the contrast signal.

Experiment 6: The window-shade illusion

In the previous experiments, we demonstrated the induced contrast asynchrony across two separate disks. Here we show how the same principle (in-phase luminance signal and anti-phase contrast signal) can create a new set of visual illusions within a single modulated disk. The stimulus configuration is shown in Figure 8. In the center is a single disk with a mean luminance of 40 cd/m² modulated sinusoidally (between 25 and 55 cd/m² at 2 Hz). The surround is a

split annulus, with half being 20 cd/m² and the other half 60 cd/m². As the disk modulates in luminance, the contrast signal at the dark edge modulates in phase with the luminance modulation, and the contrast signal at the light edge modulates in anti-phase with the luminance modulation.

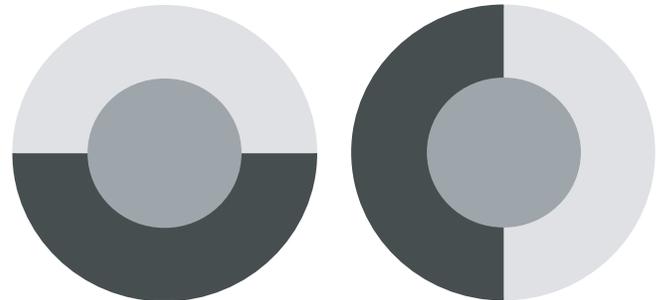


Figure 8. The spatial configurations for the window-shade illusions. The center disk was modulated at 2 Hz. The surround light was a thick annulus split so that one half was light and the other half was dark. The rocking-disk illusion occurs when the surrounds are thin. Click on the image to see an interactive demonstration.

We examined the effect of a thick surround oriented vertically and thick surround oriented horizontally. The direction of modulation appeared orthogonal (or nearly orthogonal) to the direction of the split: In the condition with a vertically split surround, a veil seemed to cross back and forth across the disk horizontally. In the condition with a horizontally split surround, the veil seemed to cross back and forth across the disk vertically. We therefore refer to this phenomenon as the window-shade illusion.

Observers

The observers were 15 college students and one university administrator. All observers had normal acuity or were optically corrected.

Procedure

At the beginning of the trials, we showed observers the conditions in Figure 8 and one condition with no surround. In order to clarify our terminology, we discussed what we meant by shading (i.e., an inhomogeneous change in lightness moving across the center disk). The stimuli contained disks of .25, .5, 1, 2, 4, or 8-deg diameter; each of these had a thick annular surround (1.5 times the diameter of the disk) that was split vertically or horizontally. The order of presentation was generated by the MatLab randomization routine. Observers viewed each presentation for 5 s, and then were asked whether the disk appeared to be shaded and whether the direction of shading was left-right or up-down.

Results and conclusion

The results are listed in Table 1. There were 16 naïve observers in each condition. Each row shows the diameter of the disk, and the columns show the items to which the

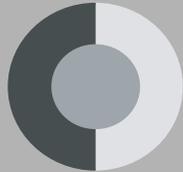
	Horizontal split		Vertical split	
				
Diameter of disk (deg)	Number of observers who reported shading effect	Number of observers who reported shading in an Up/Down direction	Number of observers who reported shading effect	Number of observers who reported shading in a Left/Right direction
.25	13	13	12	11
.5	15	15	15	15
1	15	15	14	14
2	16	16	16	16
4	15	15	15	15
8	13	13	16	16

Table 1. The number of observers out of 16 who reported that they perceived the shading effect, and whether they saw the shading motion as moving in an up/down direction or in a left/right direction. The effect was measured for six different disk diameters and for a vertical and horizontal split in the annulus.

observers responded. Each cell reports the number of observers (out of 16) who gave a positive response to a particular item. For most observers, the results agreed with the visual inspection of the stimulus described above. Almost all observers (12 to 16, depending on the diameter of the disk) reported that the modulated disks appeared to be shading. The shading effect appeared at all disk diameters that we measured.

Discussion

We have presented a new type of visual effect that depends on the temporal separation of in-phase luminance signals from anti-phase contrast signals. The effect can be produced by a thick or a thin annulus. We show that temporal frequency and modulation amplitude are important parameters for determining the relative strength of the contrast and luminance signals. We also show that the principle can be applied within a single disk to produce the window-shade illusion.

It is possible that the appearance of the asynchrony reflects the underlying temporal sensitivity of the contrast system. On the other hand, our tasks required observers to make subjective judgments concerning the appearance of the modulation. The variety of responses could therefore be due entirely to observer bias for anti-phase signal over the luminance signal or vice versa. Indeed, just as is the case for any ambiguous figure where observers can switch between one view and the next, observers who thought that the 1-Hz stimulus appeared in phase would acknowledge the presence of the anti-phase signal. We have not been able to create a task that overcomes the subjectivity issues because the stimulus always contained both contrast and luminance information; judgments concerning one aspect of the stimulus always take place in the presence of the other.

One partial solution is to null the contrast of the signals by changing the color angle of modulation (Shapiro & D'Antona, 2003), but such judgments, too, are perceptually based (adjust until the signal appears only in-phase) and not performance based (such as a forced-choice task).

We can say, however, that the ambiguous nature of the stimulus appears to be most noticeable at low frequencies. At 1 Hz and at low modulation amplitudes, observers can report that the modulation appears both in phase and out of phase, but at higher frequencies and higher modulation amplitude, observers had difficulty perceiving an in-phase signal.

One possible reason for this is that the perceptual interpretation depends on the relative strength of response to the primary and contrast signals. The process that responds to the primary signal has a lower saturation level, so at higher modulation levels the contrast signal predominates. Such an interpretation is not far from Spehar and Zaidi (1997), who argue that temporal sensitivity is determined by whether the visual system is more sensitive to internal modulation or to edge modulation. Cast in terms of a signal detection-like model, at 1 Hz or low modulations, both the anti-phase and luminance signals produce responses that have equal weighting (a small d'), so a small difference in observer criterion will have a large effect on the proportion of in-phase versus out-of-phase responses; at 3 Hz, the anti-phase signal is predominant (a large d'), so observer criterion will have much less of an effect on the proportion of out-of-phase responses.

The induced contrast asynchrony demonstrates that at low temporal frequencies, a low spatial frequency signal arising from the center of the disk can be separated perceptually from a high spatial-frequency signal arising from the edge. The ability to represent both the contrast and luminance signals suggests that two separate representations occur at a relatively advanced stage of visual processing. The

results presented here cannot distinguish whether the separation begins early in visual processing and continues through the cortex, or whether the separation originates late in visual processing.

In response to a reviewer's comments, we have called the two-disk asynchrony a *visual effect* because the in-phase or anti-phase appearance corresponds to the physical stimulus, and we have called the window-shade and rocking-disk asynchronies *illusions* because there is no obvious correspondence between the perception and the physical stimulus. This distinction between effect and illusion depends entirely on the problematic conception of what it means to be veridical (i.e., why should perceptual correspondence to a luminance signal be considered veridical, whereas perceptual correspondence to a specifiable combination of contrast and luminance signals is not?). The effect/illusion distinction should therefore be regarded with some caution.

The principle underlying these effects is robust and can be generalized to a wide variety of spatial configurations. For instance, variants of the effect can be created when the temporal modulation takes place adjacent to, or surrounding, a spatial luminance ramp. Curiously, when the ramp is thin, the modulating field appears to shift position in a manner similar to that shown in the *rocking-disk* illusion. This suggests that illusory motion may be a general feature of the induced contrast asynchrony phenomena when there is a single modulating field and the contrast edges are thin and also suggests a relationship between these effects and those of Kitaoka, Pinna, and Brelstaff (2004), who used contrast polarities to determine the direction of tilt in the Café Wall/Münsterberg illusion. Another variant of the effect, which was pointed out by Adam Reeves of Northeastern University, consists of two modulating disks and a background of a fixed luminance: The mean luminance level of one disk is higher than the background level, and the mean luminance of the other is below the background level. In this condition, the apparent modulation is asynchronous even though the apparent depth of modulation is greater for the darker circle.

To the best of our knowledge, the basic principle behind induced contrast asynchrony has not been shown before, although some researchers have manipulated temporal aspects of a contrast signal to produce interesting visual effects (Anstis 2001; Anstis & Ho 1998), some have examined the effects of modulating the surrounding lights (De Valois, Webster, De Valois, & Lingelbach, 1986; Rossi & Paradiso, 1996; Singer & D'Zmura, 1995; Zaidi, Yoshimi, Flanigan, & Canova, 1992), and others have used alternate luminance background configurations to investigate apparent motion (Gilroy and Hock, 2004; Hock et al, 2002;).

Shapiro and D'Antona presented the effect at the annual meeting of the Visual Sciences Society (2003). The presentation (click [here](#) for a PDF version of the poster) contained the results from experiments in which observers were asked to change the color modulation in order to null the asynchrony. We showed how the stimulus may prove useful as a photometric technique, as a diagnostic method

for finding individual differences in color perception, and as a method for delineating independent directions in color space. We also showed the curious behavior of the contrast asynchrony in White's effect and in contrast-contrast induction. The principles underlying contrast asynchrony may prove useful for investigating a wide variety of visual processes.

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