Chapter 41. The contrast illusion

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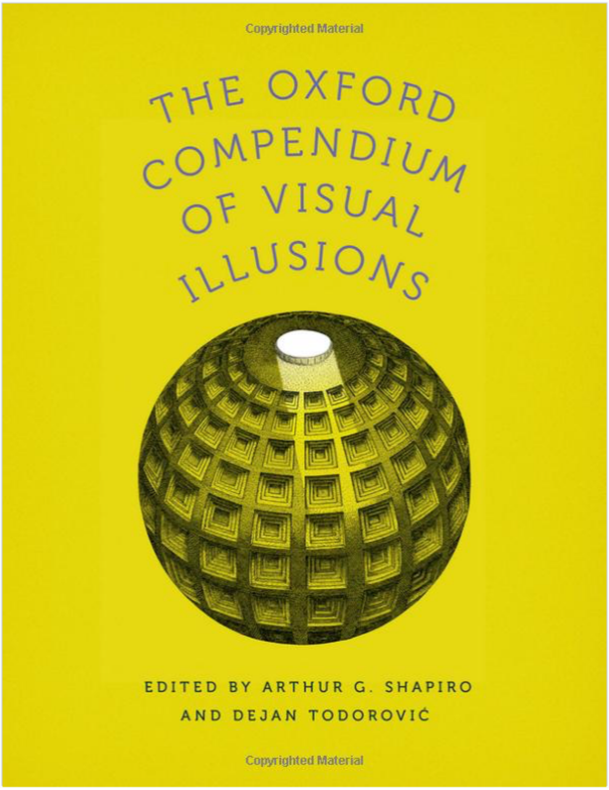

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Chapter 41
The Contrast Illusion

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INTRODUCTION

The contrast contrast illusion is shown in its basic form in Figure III.41-1a (Chubb, Sperling, & Solomon, 1989). The two central disks of texture on the left and right are physically identical. However, to most observers, the left one (appearing on the mean gray background) appears higher in contrast than the right one (appearing on the high-contrast texture background).

The contrast contrast illusion is analogous to the classical simultaneous contrast illusion shown in the small image inset in the left side of Figure III.41-1a. In this figure, the two disks are physically identical; however, the one on the left (seen against a black background) appears brighter than the one on the right (seen against a white background). This illusion illustrates that the brightness of a homogeneous test patch depends dramatically on the context in which the test patch is situated. The contrast contrast illusion shows that the same is true of the apparent contrast of a textured test patch: a test patch filled with medium-contrast texture appears higher in contrast when viewed against a homogeneous gray field (which we can think of as a background texture of contrast zero) than it does against a background field filled with high-contrast texture.

A standard account of the simultaneous contrast illusion (first given by Mach, 1866) proposes that the neurons registering the intensity of light impinging on nearby points of the retina laterally inhibit each other. Thus, for example, the neurons stimulated by the light from the test patch on the right side of the small image inset in Figure III.41-1a are inhibited by the more strongly activated neurons stimulated by the white background. By contrast, the neurons stimulated by the light from the test patch on the left side of the inset in Figure III.41-1a receive no such inhibition from the neurons stimulated by the black background; as a result, the patch on the left appears brighter than the patch on the right. Most of the computational models offered to account for the contrast contrast effect (e.g., Chubb, Sperling, Solomon, 1989; Heeger, 1994; Singer & D'Zmura, 1995) are analogous to Mach's (1866) lateral inhibition model of brightness perception.

SENSING TEXTURE CONTRAST

To grasp the spirit of this model, however, it is necessary first to understand how the visual system senses the contrast of a texture. To measure the intensity of a light, one might use a simple meter that counts quanta impinging on a region of the retina per unit time; indeed, retinal receptors (rods and cones) do something like this. This strategy will not work to measure the contrast of a texture for the simple reason that one can increase the contrast of a texture without changing the average light intensity of the texture. As the bright points of the texture are increased in intensity, the dark points are decreased so that the average intensity does not change. To gauge the contrast of a texture, one must extract from the image of the texture a statistic that reflects the strength with which intensities *vary* inside the texture.

Many different neurons in the visual processing stream provide potential access to information about texture contrast. At the level of the retina, on-center retinal ganglion neurons (on-cells) and off-center retinal ganglion neurons (off-cells) will both capture information about texture contrast in the sense that each population of neurons will fire more strongly in response to high-contrast than to low-contrast texture. The reason is simple, as we illustrate first in the case of on-cells.

As shown by the magenta lines in Figure III.41-2a, an on-cell has a receptive field with a small excitatory central region (i.e., light impinging on this region tends to increase the firing rate of the neuron) and a larger, doughnut-shaped, inhibitory surround (i.e., light impinging on this region tends to decrease the firing rate of the neuron), and the on-cell's response will be roughly proportional to the difference between the average intensity of the light impinging on its center versus its surround *provided* that this difference is positive (i.e., provided the light impinging on its center is more intense than on its surround); if the difference is negative, the on-cell will not fire at all. Because the light inside the central magenta circle in Figure III.41-2a is brighter than the light falling in the doughnut-shaped surround, an on-cell whose receptive field matched the one illustrated here would fire strongly.

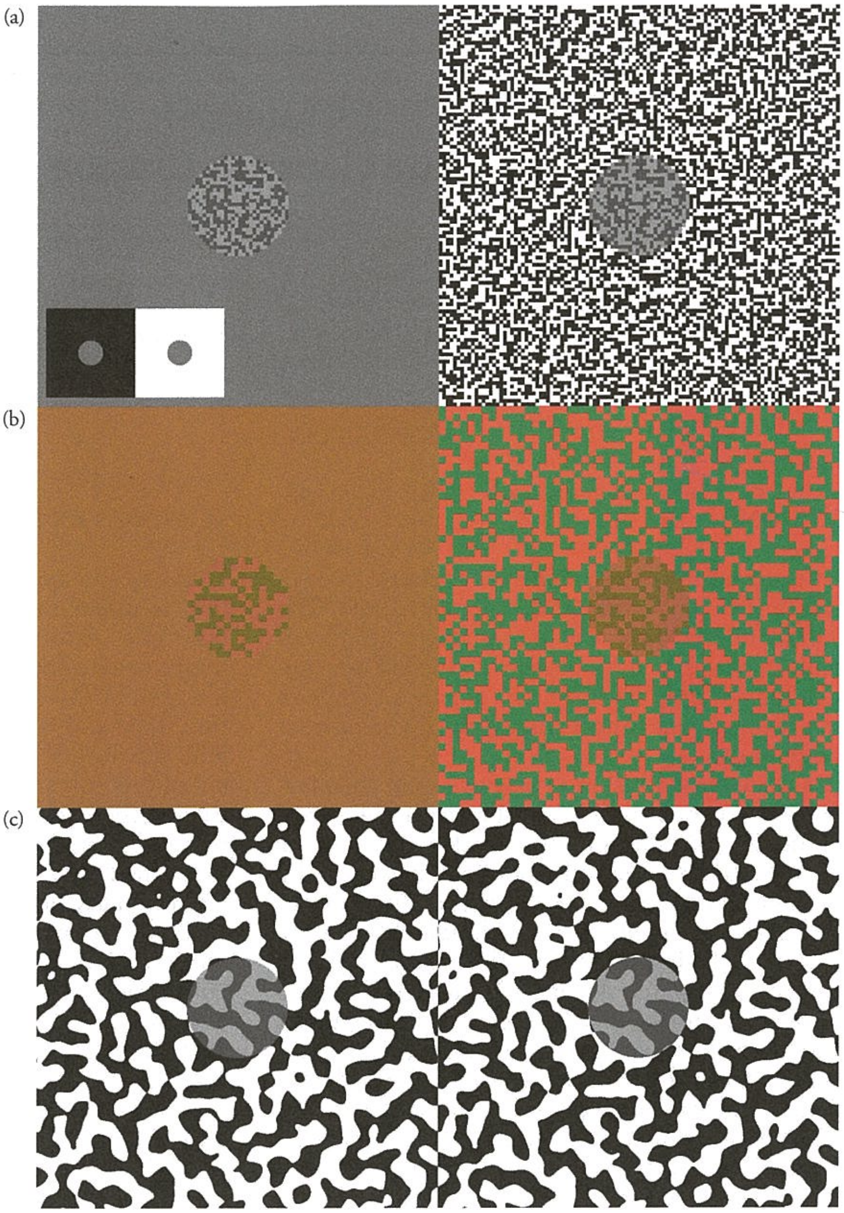

Figure III.41-1. Three variants of the contrast contrast illusion. In each case, the test disks appearing on each of the left and right sides are physically identical; however, to most observers the disks on the left appear higher in contrast than the disks on the right. (a) A medium contrast disk of achromatic texture appears higher in contrast when it appears against a uniform gray background than it does when it appears against a high-contrast texture background; this display is analogous to the simultaneous contrast display inset into the left side. (b) A medium contrast disk of equiluminant, red-green texture appears higher in contrast when it appears against a uniform brown background than it does when it appears against a high-contrast texture background. (c) If the disk can be interpreted as a translucent (right panel), its texture appears lower in contrast than it does if boundary cues preclude such an interpretation (left panel).

An off-cell works like an on-cell except that its surround is excitatory and its center is inhibitory. As this implies, the off-cell will respond above zero only if the light hitting its central region is lower in intensity than the light hitting its surround. Thus, for example, an off-cell with the receptive field indicated by the green lines in Figure III.41-2a would give a strong positive response because the light hitting its center is lower in intensity than the light hitting its doughnut-shaped surround.

Why does the visual system use both on-cells and off-cells? It seems it would make more sense to use just one type of neuron whose firing rate was proportional to the difference between the average light intensity in the central, excitatory region minus the average light intensity in the doughnut-shaped surround. Although this strategy seems natural, it implies that whenever the light in the central region is lower in intensity than the light in the surround, the neuron must be able to lower its firing rate below zero, which in turn implies that the neuron must maintain a resting firing rate (the firing rate that signals equal light levels in center and surround) that is greater

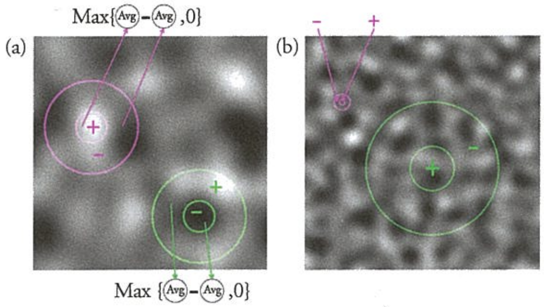

Figure III.41-2. How on- and off-center neurons respond to texture. (a) The magenta lines show the computation performed by a (strongly activated) on-center neuron, and the green lines show the computation performed by a (strongly activated) off-center neuron. (b) If the receptive field of an on-center neuron is too small (magenta) or too large (green) relative to the granularity of the texture, then the neuron will not be strongly activated.

than zero. The problem is that it takes resources to produce action potentials; thus it would be very wasteful for the visual system to use large arrays of neurons whose resting firing rate were elevated substantially above zero. Instead, the visual system avoids this waste by using separate channels (on-cells and off-cells), each with a resting firing rate of zero, for conveying information about positive versus negative deviations of light intensity away from the local average light level (Hubel, 1960; Kuffler, 1953).

Each population of neurons, the on-cells and the off-cells, provides information about texture contrast. This is illustrated in Figure III.41-3. Panel (a) shows a version of the contrast contrast illusion. Note that all of the main components of this figure (the homogeneous gray background on the left, the high-contrast texture background on the right, and the test disk of medium-contrast texture reproduced in the middle of each side of panel [a]) have equal average light intensity; blacks and whites vary symmetrically around mean gray. Panel (b) shows (downscaled in size) the pattern of output that results from applying a dense array of on-cells to the stimulus in panel (a). Each pixel value in this image represents the firing rate of an on-cell whose receptive field is centered at the corresponding pixel of panel (a). A firing rate of zero is coded by the same gray that is used for the homogeneous background in panel (a), and on-cell responses greater than zero are coded by grays of increasing brightness. Panel (c) shows the analogous pattern of output from a dense array of off-cells.

Note that regions of increasing texture contrast in panel (a) result in regions of increasing average activation in each of panels (b) and (c). The homogeneous gray background on the left side of panel (a) produces a homogeneous region of response zero from each of the on-cell and off-cell neural arrays. The test disk reproduced on both sides of panel (a) produces a smattering of medium-level activation in each of the on-cell and off-cell neural arrays, and the high-contrast texture background on the right of panel (a) produces a smattering of higher activation in each of the two arrays.

Note, however, that if any given pixel in the "neural image" (Robson, 1980) produced by the on-cells is non-zero, then the corresponding pixel in the off-cell neural image must be zero and vice versa. As this observation suggests, we can obtain a neural image whose local average level of activation signals contrast more continuously over space by adding the images in panels (b) and (c) together. The resulting image is shown in Figure III.41-3d. Many neurons in primary visual cortex (e.g., complex cells; Hubel & Wiesel, 1962) operate by additively combining on-cell and off-cell responses.

Suppose there exists in human visual cortex an array of neurons whose response to the contrast contrast stimulus shown in Figure III.41-3a is the neural image shown

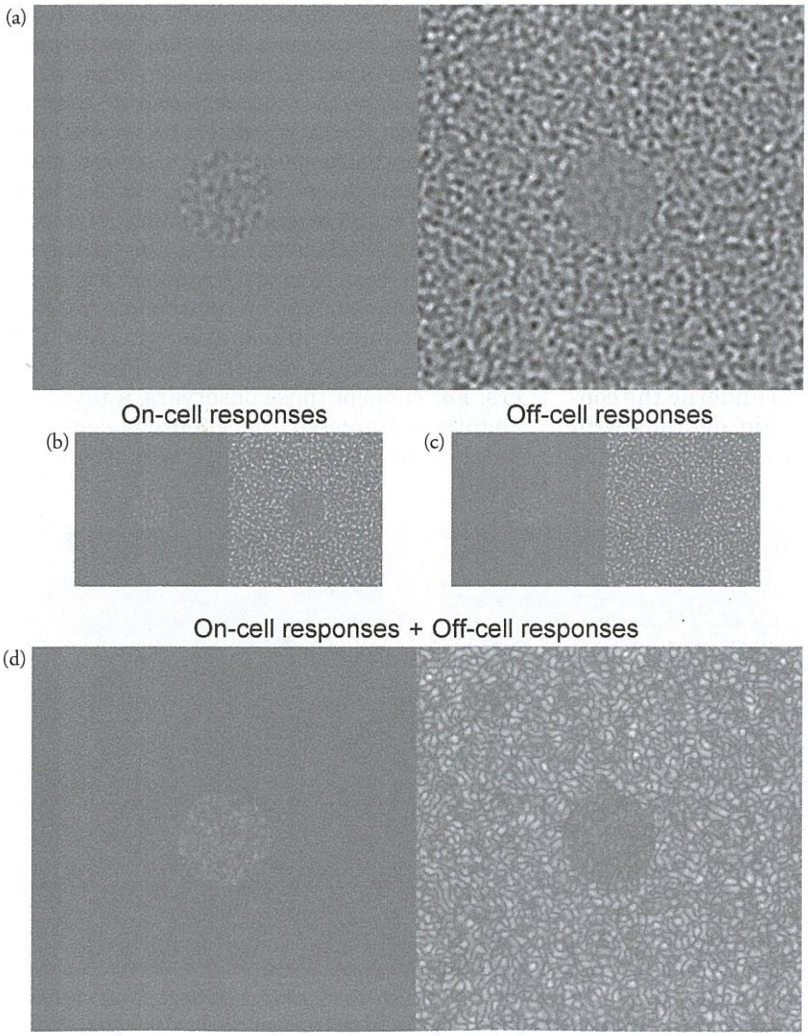

Figure III.41-3. How on- and off-center neurons could convert the contrast contrast display into a neural image akin to the simultaneous contrast display. (a) A version of the contrast contrast display. (b) Responses of on-center neurons to the image shown in (a). (c) Responses of off-center neurons to the image shown in (a). (d) The sum of the images in (b) and (c)—note the similarity between this image and the simultaneous contrast display inset in the left side of Figure III.41-1a.

in Figure III.41-3d. In itself, the existence of such a neural array does not explain the contrast contrast illusion. We must further hypothesize that the response of a given neuron in this array operates to suppress the responses of on-cells and off-cells whose receptive fields are in the same retinal neighborhood as the receptive field of the neuron. If this is the case, then the neurons monitoring the region of the visual field filled with the homogeneous gray background on the left in Figure III.41-3a will (as we see in Fig. III.41-3d) remain silent; by contrast, the neurons stimulated by the high-contrast texture background on the right will fire strongly. This means that the on-cells and off-cells sensing the test disk on the right will be inhibited much more strongly (from the highly activated neurons monitoring the nearby, high-contrast background texture) than the neurons sensing the test disk on the left.

THE IMPORTANCE OF TEXTURE GRANULARITY

In generating the images in Figures III.41-3B, C, and D, we used on-cells and off-cells whose receptive fields are matched in scale to the granularity of the texture being viewed. The receptive field centers of these on- and off-cells are roughly equal in size to the blobs in the texture (as is evident in Fig. III.41-2a). Figure III.41-2b shows what happens if this were not true. If the granularity of the texture were too fine relative to receptive field scale (as is the case for the receptive field indicated in green), then regardless of how the receptive field happened to align with the texture, its response would be very near zero because bright and dark variations within the receptive field center as well as in the receptive field surround would tend to average out to the same value. On the other hand, if the texture were too coarse relative to the receptive field scale (as is the case for the on-center receptive field indicated in magenta), then regardless of how the receptive field happened to align with the texture, its center and surround would be stimulated by light of approximately uniform, equal intensity, implying that its response would again be very near zero.

If the lateral inhibition hypothesized to underlie the contrast contrast illusion occurred only within neurons with receptive fields of a fixed spatial scale, then the suppression of the apparent contrast of the test patch in a contrast contrast display should be weakened when the granularity of the surrounding texture did not match the granularity of the texture in the test patch. In Figure III.41-4 the test patch is identical in the left, center, and right displays. However, the three background textures differ in granularity: the left background texture is twice as fine as the test patch; the center background is equal in granularity to the test patch; and the right background texture is twice as coarse as the test patch. Chubb, Sperling, and Solomon (1989) showed that, indeed, the apparent contrast of the test patch is suppressed more strongly (by roughly a factor of 2) when the granularity of the background matches that of the test patch than in either of the two cases shown on the left and right sides of Figure III.41-4 in which the granularity of target and background differ by a factor of 2.

INDIVIDUAL DIFFERENCES

Of course it can be difficult—if not impossible—to measure apparent contrast (or apparent anything, for that matter) without contamination from cognitive biases and/or expectation effects. What we can say for sure is that there are several results consistent with substantial individual differences in how the contrast contrast illusion seems to be experienced. Cannon and Fullenkamp (1993) reported one participant for whom the basic contrast contrast effect was dramatically reversed. For this participant, embedding a low-contrast patch of texture in a high-contrast background actually made the contrast of the texture patch appear higher than it did when it was viewed against a homogeneous gray background. For a second participant, embedding a small target texture patch in a larger surrounding texture of equal or lower contrast enhanced the contrast of the texture patch compared to the no-surround condition.

Nonetheless, surround-induced enhancement of apparent contrast seems to be relatively rare. Bosten and Mollon (2010) measured the contrast contrast illusion (and nine other illusions) in a pool of 100 normally sighted observers. For some of these observers, a textured surround only slightly suppressed the apparent contrast of the texture patch it contained; for others, it strongly suppressed the

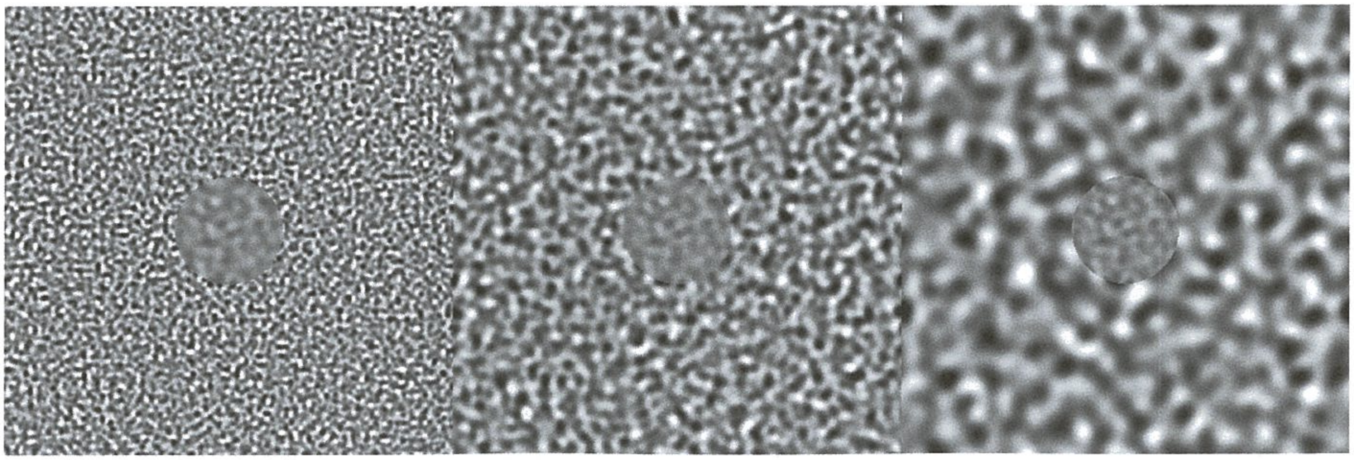

Figure III.41-4. How the granularity of the background texture influences the illusion. The background texture on the left (right) is finer (coarser) than texture in the test patch. Most observers judge the contrast of the right and left test patches to be higher than that of the central test patch, which is matched in granularity to its background texture.

apparent contrast of the target; but for none did it actually enhance the target's apparent contrast. Across observers, a correlation was found between the strength of this suppression and that caused by chromatic (red/green) contrast, but there was no significant correlation between the basic (luminance) contrast contrast effect and any of the other eight illusions studied.

Dakin, Carlin, and Helmsley (2005) reported results from 11 forensic inpatients for whom the basic contrast contrast effect was weak or absent. All of the observers suffered from schizophrenia. Yang et al. (2012) recently replicated this basic result in 30 outpatients. Dakin et al. hypothesized that abnormally low lateral inhibition may be related to both the reduced contrast contrast illusion and schizophrenia. However, two later studies of 132 outpatients with schizophrenia or schizoaffective disorder found neither a significant difference between the strengths with which normal observers and these patients experience the contrast contrast effect (Barch et al., 2012) nor any relationship between the severity of schizophrenic symptoms and the strength of the contrast contrast illusion (Gold et al., 2012).

IS THE CONTRAST CONTRAST ILLUSION SELECTIVE FOR CONTRAST POLARITY?

In our previous discussion (see Fig. III.41-2) we suggested that the contrast contrast illusion might be mediated by neurons that sum the responses of on-cells and off-cells together to create a neural image whose response strength at a given point reflects the contrast of the texture in the neighborhood of that point. Under this hypothesis, the neural substrate that gives rise to the illusion has discarded all information about whether the contrast registered at a particular point was signaled by an on-cell or an off-cell (i.e., whether luminance deviated negatively or positively from the local average). Is this true?

Although the textures we used in the stimulus displays in Figures III.41-1a, III.41-2a, and III.41-4 drive on-cells and off-cells with equal effectiveness, it is possible to create textures that activate one of these two classes of neurons more strongly than the other. This is exactly what Sato, Motoyoshi, and Sato (2012) did. Their stimulus textures are shown in Figure III.41-5. Each of these textures contains either dark vertical elements or bright vertical elements on a gray background. The textures with the bright bars are designed to stimulate on-cells more strongly than off-cells and vice versa for the textures with the dark bars. Notice that the backgrounds differ in their brightnesses; the brighter the vertical elements, the darker the background. This is to ensure that all of the textures have the same the average light intensity.

Compare the rightmost upper and lower stimuli. Most likely, as the participants Sato et al. (2012) used in their experiments experienced, the central patch of texture in the upper rightmost stimulus will appear lower in contrast than the (equal contrast) patch of texture in the lower rightmost stimulus. Sato et al. conclude that on-cells are laterally inhibited by on-cells more effectively than they are by off-cells, contradicting the hypothesis (see Fig. III.41-5) that the site of the inhibition is a neural substrate in which on-cell and off-cell responses have been additively combined.

Notice that the difference in the apparent contrast of the central texture patches in the stimuli on the far left of Figure III.41-5 is less dramatic than it is in the stimuli on the far right. Sato et al. (2012) suggest that the reason for this is that on-cells are strongly activated by both the background textures in the upper and lower leftmost stimuli; as the texture elements are made denser, the differential activation of on-cells versus off-cells is weakened. A density effect of this sort may have undermined the efforts of Solomon, Sperling, and Chubb (1993), who addressed this same issue but found that textures designed to

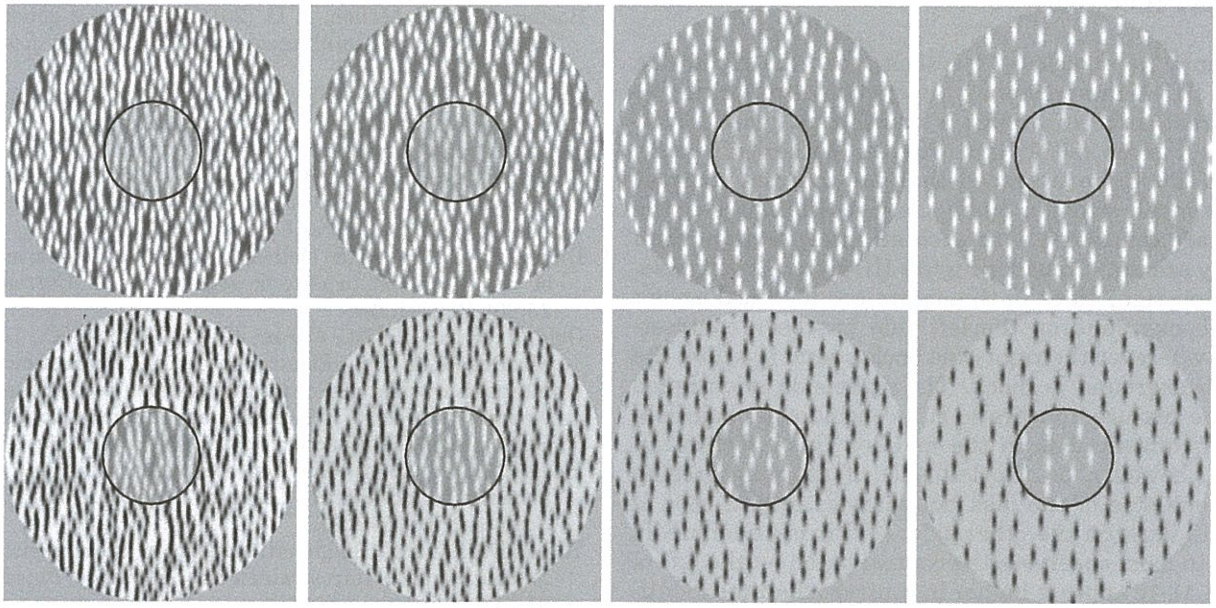

Figure III.41-5. Is the contrast contrast illusion selective for contrast polarity? Most observers judge the test disks in the two rightmost lower panels to be higher in contrast than the corresponding test disks in two rightmost upper panels. This suggests that the contrast contrast illusion is stronger if the polarity of the background texture matches that of the target texture. (Figure reproduced with permission from *Journal of Vision.*)

differentially activate on-cells versus off-cells were equally effective at suppressing the contrast of each other.

COLOR AND THE CONTRAST CONTRAST ILLUSION

It is possible to create powerful contrast contrast effects using displays in which texture varies across space not in light intensity but rather in color. An example is shown in Figure III.41-1b. The textures used in this figure are approximately uniform in their luminance (their effective light intensity for human vision); instead, they vary in their chromatic contrast. The background texture on the right varies strongly between a red and a green that are roughly equiluminant, and the texture patch reproduced on the left and right sides of the display varies less dramatically. Most observers perceive the texture disk on the left to be higher in chromatic contrast than the disk on the right.

Contrast contrast effects have been studied extensively by Singer and D'Zmura (1994) using textures modulating not only achromatic light intensity but also color. They used textures that modulate between high and low luminance as well as textures that modulate between equal intensity (equiluminant) red and green and other textures that modulate between equal intensity blue and yellow. They tested how strongly each of these types of texture suppresses the perceived contrast (either color contrast or intensity contrast) of a central test patch of each type. Their studies revealed that each type of texture is most effective at suppressing the contrast of a test patch of the same type of texture; however, substantial suppression also occurs across different types of texture (with the exception that equiluminant color modulations exert very little influence on the perceived contrast of achromatic texture).

ECOLOGICAL ACCOUNTS OF THE CONTRAST CONTRAST ILLUSION

Readers may be struck by the sense that the right side of Figure III.41-1a appears as though they are looking at high-contrast texture through a translucent plastic disk. Lotto and Purves (2001) and Purves, Williams, Nundy, and Lotto (2004) have argued that the contrast contrast illusion is much stronger when the visual features of the stimulus are consistent with such an interpretation than when they are not. Consider Figure III.41-1c, for example. The left and right sides in this figure are identical except that the background on the left side has been contrast-reversed: wherever the right-side background is white, the left-side background is black. The right side is designed so that the texture appears to run continuously behind a translucent plastic disk in the middle. This effect is undermined, however, on the left side: if an image region abutting one side of the disk boundary is bright, then it switches to dark on the other side. And it is undoubtedly true that to most observers the central patch on the left of Figure III.41-1c appears higher in contrast than the identical patch on the right.

Lotto and Purves (2001) and Purves et al. (2004) observe that if indeed the image projected to the retina were the result of seeing high-contrast texture through a translucent disk, then the ways in which light interacts with surfaces would mandate that the contrast of the image region subtended by the disk should be low. However, if instead the image were the result of light reflecting directly from a textured surface whose reflectance properties changed at the disk boundary, then no constraints would operate to restrict the contrast of the texture inside the disk. They argue that, in the automatic processing it performs prior to any conscious reflection on the part of the observer, vision comes to embody this knowledge about the probable causes of the image projected to the retina. Why does the disk on the left side appear lower in contrast? It is because the features in the image make it likely that the distal cause of the image is a translucent disk through which high-contrast texture is being seen (Lotto & Purves, 2001; Purves & Lotto, 2003; Purves et al., 2004).

If Lotto and Purves (2001), Purves and Lotto (2003), and Purves et al. (2004) are correct, then models based strictly on lateral inhibition are unlikely to suffice to account for the contrast contrast illusion because such models do not take into account the full scope of stimulus features that reliably signal that the stimulus results from viewing a textured background through a translucent disk. Some of the displays they have created offer striking support for this claim. It is important to realize, however, that regardless of whether this theory is true, one is still left with the problem of modeling the computations that occur within the visual system that give rise to the contrast contrast illusion.

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