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Contrast contrast: interactions between spatial and luminance factors

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The apparent contrast of a pattern is lower when it is surrounded by patterns with high physical contrast than when surrounded by lower-contrast patterns. This "contrast-contrast" phenomenon has been attributed by previous investigators to neural interactions among contrast gain signals. We report measurements of several cases that seem to be more consistent with transparency and lightness constancy mechanisms than with pattern-specific neural interactions.

Spatial factors in contrast-contrast

Random visual texture and spatial frequency specificity of contrast-contrast. Chubb, Sperling & Solomon (1989) found that a test patch of random visual texture has lower apparent contrast when surrounded by a high-contrast background of similar texture than when surrounded by a uniform gray field (Figure 1a). They called this brightness phenomenon "contrast-contrast" in analogy with classical simultaneous brightness contrast (Figure 1b). The phenomenon shows that brightness at a point in the image is a more complex function of the surrounding image structure than had previously been suspected. The lower apparent contrast of the test patch surrounded by high contrast texture cannot be attributed to the mechanisms responsible for simultaneous brightness contrast because the space average luminance of the test patch and surrounds are equal.

To measure contrast-contrast Chubb et. al. temporally modulated the physical contrast of the surrounding texture, thereby inducing a temporal modulation of the apparent contrast of the test patch. The subject added a physical modulation in counterphase to null the apparent modulation. They found that the induced modulation was (1) strictly monocular and (2) spatial frequency specific. Their proposed explanation had two premises. First, the apparent contrast at a point in space was assumed to depend on the combined responses of multiple neural units spatially corresponding to that point, each tuned to a specific band of spatial frequencies. Second, the response of each unit was assumed to be normalized relative to the responses of units with the same spatial frequency tuning corresponding to nearby spatial locations.

Sinusoidal gratings: Spatial position and orientation effects in contrast-contrast. In an earlier study, Ejima & Takahashi (1985) measured the apparent contrast of a rectangular patch of vertical sinusoidal grating in the simultaneous presence of immediately adjacent èinducing gratings. The physical contrast, relative phase and relative position of the sinusoidal inducing gratings were varied with respect to the test grating. They presented evidence that the contrast depression depended on the relationship between the physical contrasts of the test and peripheral gratings, rather than their absolute physical contrasts. The apparent contrast was enhanced for physical inducing contrasts below that of the test grating, but suppressed for peripheral contrasts above the test grating contrast. The enhancement effect decreased as stimulus contrast increased, while suppression effect was relatively constant with contrast.

The relative spatial positions of the test and inducing gratings also affected the apparent contrast of the test grating. When the peripheral gratings were horizontally adjacent to the test grating, the contrast-contrast was obtained, irrespective of the phase relationship between the two gratings. The same dependence on relative physical contrasts was observed when the peripheral gratings were vertically adjacent to the test grating, but only for the in-phase condition. In the out-of-phase condition test apparent contrast increased monotonically as a function of the peripheral physical

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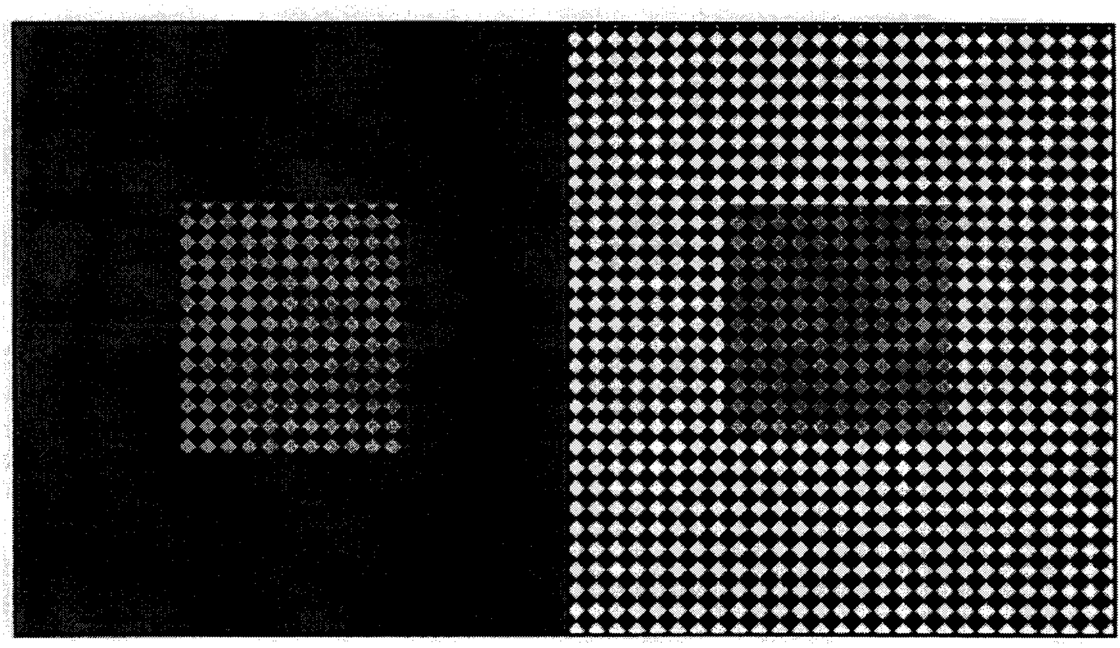


Figure 1. a. Contrast-contrast: the two central textured patches are identical, with Michelson contrast = 0.5. The left textured patch has higher apparent contrast than the right.

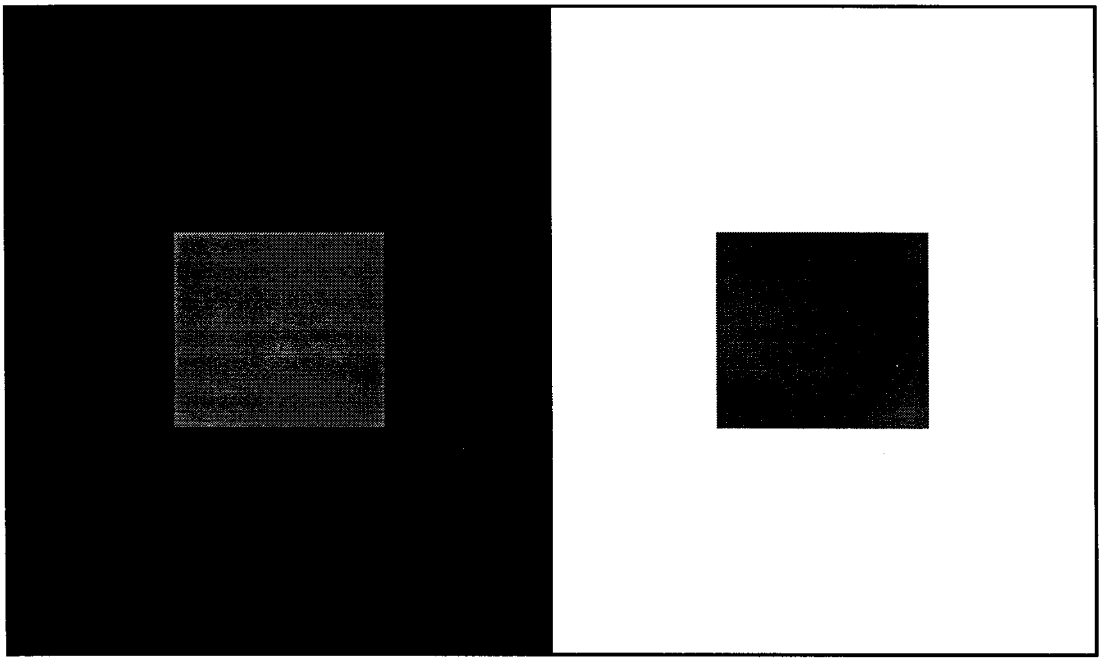


Figure 1. b. Simultaneous brightness contrast: the two central gray patches have the same luminance, but the left gray patch appears brighter than the right.

contrast. These orientation asymmetries were attributed to the characteristics of the borders formed between the test and peripheral gratings.

Cannon & Fullenkamp (1991) found that surround gratings of both higher and lower physical contrasts lowered the apparent contrast of the central patch. The suppression of apparent contrast declined with increasing spatial separation between the gratings and with increasing spatial frequency separation. It also declined sharply as the orientation difference increased to 15 degrees and more slowly for further increases. Cannon & Fullenkamp (1991) interpreted this as indicating that inhibitory weighting functions in contrast-contrast are controlled by two orientation components, one decreasing more rapidly in strength as the orientation difference between center and surround increases than the other. Subsequently (Cannon & Fullenkamp, 1993) they reported large individual differences in apparent contrast suggesting two different mechanisms for spatial interactions involved in apparent contrast: one that mediates enhancement and the other one that mediates suppression. The strength of the excitatory and/or inhibitory contributions from spatially distributed contrast sensitive elements varies among observes and its effects on the perception of objects in real world is unknown.

Spatial frequency independent and orientation independent factors in contrast-contrast

Contrast-contrast lightness induction. Spehar & Arend (1991) suggested that both excitatory and inhibitory apparent contrast effects are not exclusively spatial frequency and orientation specific. We want to suggest that the contrast-contrast phenomenon has a component that is not readily explained in terms of lateral interactions among narrowly tuned spatial frequency and orientation selective mechanisms. In the demonstration in figure 2 there is a difference between the brightnesses of the uniform patches lying on the backgrounds that differ only in luminance contrasts. The average mean luminances of the right and left sides are the same. The spatial frequency distributions èof the background and the uniform patches are very different. Nevertheless, all patches with luminance higher than the mean luminance of the backgrounds are brighter on the low contrast background than patches with the same luminances on the high contrast background. Also, patches with luminance lower than the mean background luminance are dimmer on the low contrast background. Thus, the brightness difference between the brightest and the darkest patches (i.e., the apparent contrast of the whole series) is greater in the low contrast surround (right side of the display) than in the high contrast surround (left side of the display). It seems plausible that the contrast-contrast phenomenon might also be described in terms of the brightnesses of the test pattern's elements: if the pattern is surrounded by a background of low luminance contrast then the more and less luminous elements of the pattern appear brighter and dimmer, respectively, than elements with the same luminances surrounded by a high contrast surround (Chubb, Sperling, & Solomon, 1989). With this interpretation/description of contrast-contrast phenomena, the connection between the contrast-contrast lightness induction and the original phenomenon does not seem totally implausible.

The contrast-contrast lightness induction effect has also been independently reported by Brown & MacLeod (1991). They displayed test patches in a variety of surrounds. Surrounds had a common mean luminance and chromaticity, but varied either in chromatic saturation, or achromatic contrast. Weakly saturated and low contrast patches in low saturation and low contrast surrounds were matched with more strongly saturated and higher contrast test patches in high saturation and high contrast surrounds. In other experiment subjects matched achromatic test spots in a black and white surround with achromatic test spots in a homogeneous gray surround. Small deviations of test spot luminances in the constant homogeneous surround were matched to much larger variations of test spots in the black and white surround. Schirillo and Shevell (1993) compared the adjustments for incremental or decremental test patches centered in either uniform surrounds or checkerboard surrounds of the same mean luminance and several levels of fixed contrast. He found that when incremental patches lie within the boundaries of the two checks' intensities, their apparent brightness increases as the contrast of the checks increases. In comparison, decrements remain relatively flat. This suggest that the space-average luminance of the checkerboard does not determine the brightness of the test patches. Since in all of the cases we mentioned here: demonstration presented in Figure 2 and in experiments of Brown & MacLeod (1992) and Schirillo (1993), the only difference that existed between different backgrounds was their contrast, it does not seem totally implausible to consider this class of effects also as a demonstration of contrast-contrast phenomena. However that would require some changes in specifications of contrast-contrast mechanism regarding its spatial frequency and orientation specificity. We propose that the contrast-contrast mechanisms is less spatial frequency and orientation specific or more broadly tuned than specified by the models of Chubb et al. (1991) and Cannon & Fullenkamp (1992).

It seems possible to account for the effect using the concept of diffusive filling-in processes from the boundary of the square (Chubb, personal communication). This diffusive filling-in boundary computations are mostly spatial frequency and orientation independent and instead of considering them as an alternative explanation of the phenomenon they seem rather likely candidate for the untuned contrast-contrast mechanism.

Proposed interactions between spatial and luminance factors in contrast-contrast. Besides the proposed untuned mechanism we want to suggest another special case of interaction between spatial and luminance factors in apparent contrast. When the central and sur-

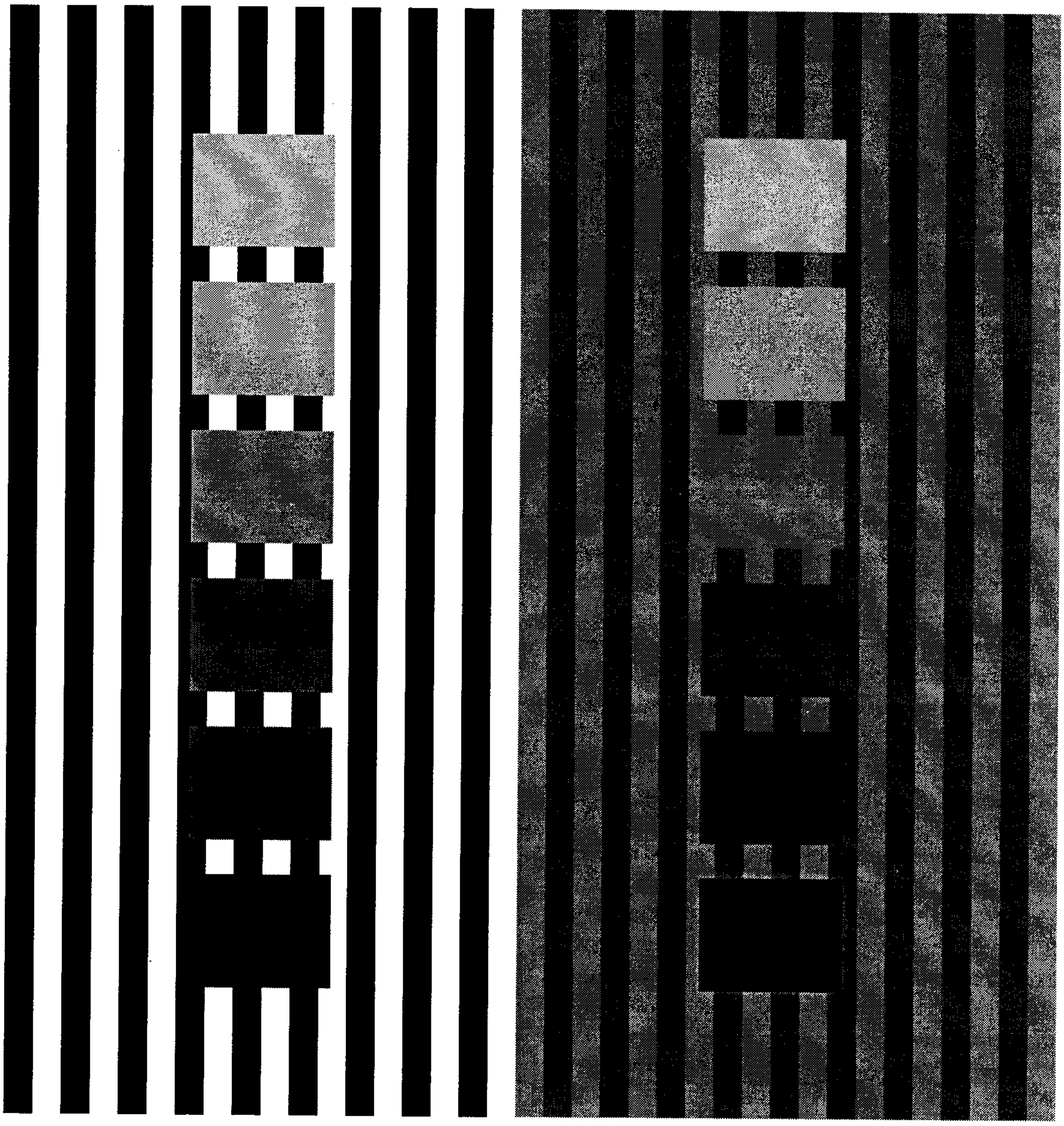


Figure 2. "Contrast brightness induction": Backgrounds on the left and right sides have the same mean luminance. Uniform patches on the left side have the same luminance as the corresponding patches on the right. However they appear dimmer or brighter in the low luminance-contrast surround than when surrounded by the high contrast surround.

round patterns have the same texture (i.e., the same spatial frequency spectrum, phase, and orientation) a more narrowly tuned, pattern-specific, mechanisms seem to be involved, including the one that we are proposing that requires very specific luminance relationships. We argue that the maximum suppression of the apparent contrast of the test patch is limited to the specific range of luminance relationships: namely the intensity of the texture elements of the test patch should lie within the range of the intensities of the texture elements of the surround. These luminance relations are compatible with the transparency percept. In that case the display has the appearance of one large, continuous texture with a superimposed veiling luminance over the region of the test patch. We propose that is the addition of this mechanism that makes the apparent contrast of the test patch a discontinuous function of the surround's luminance contrast.

There are two cases where we do not expect the involvement of the transparency-related mechanism: (1) when the luminance relationships are not compatible with perception of transparency, i.e., when the luminances of the central patch elements do not lie within the range of luminances of the surround elements, and (2) when spatial frequency and spatial orientation of the central patch and its surround are different. In

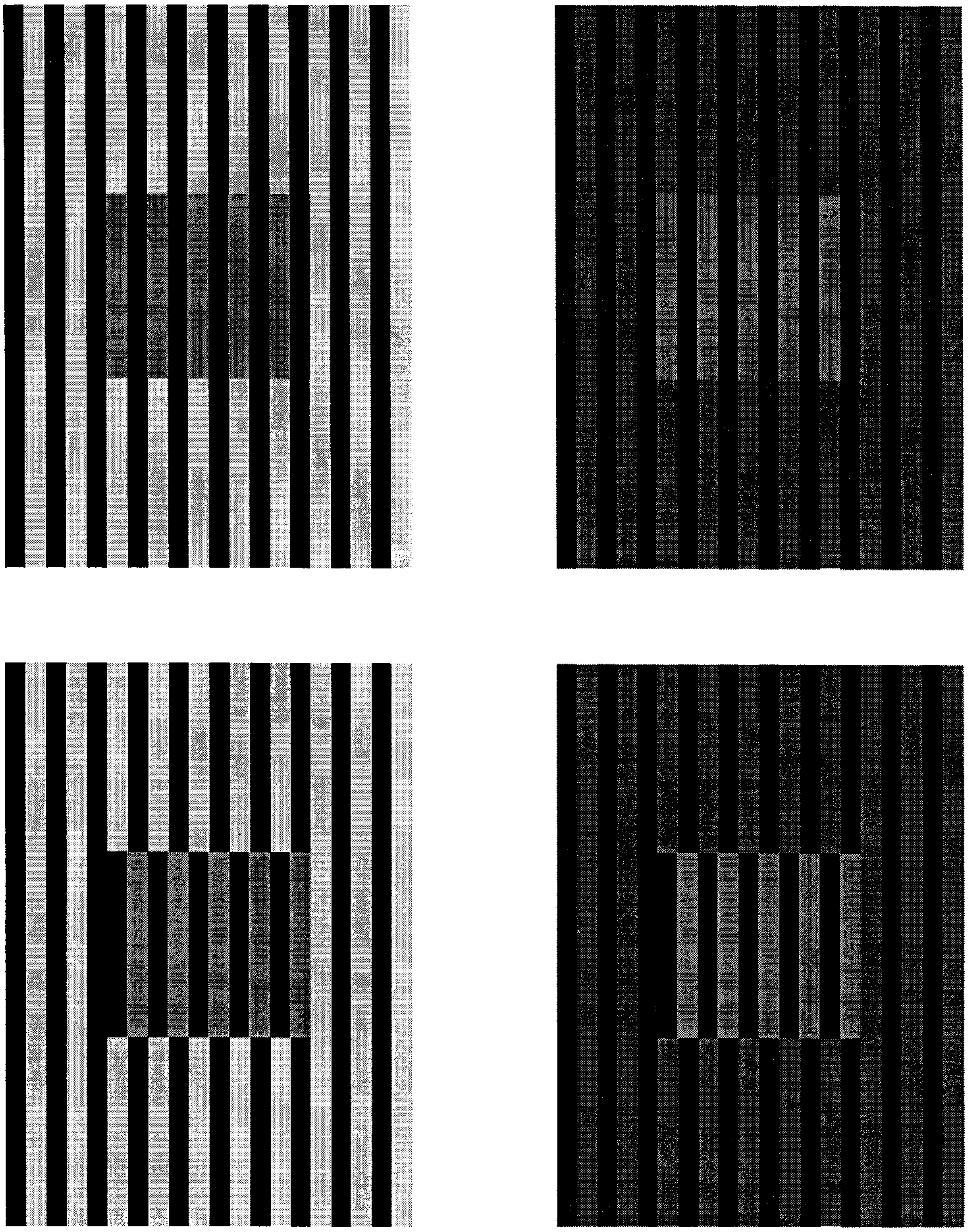


Figure 3. b. In-phase and out-of-phase square-waves.

Procedure

Observers adjusted the luminance contrast of the test patch (Figure 3a, left) to make its apparent contrast equal to that of the standard patch (Figure 3a, right). Viewing was binocular and observers were told to spend about the same amount of time looking at the test and standard patterns and to alternate their gaze between the patterns, shifting approximately once every two seconds. Five adjustments of the test patch for each of the nine levels of the surround luminance contrast of the standard patch, constituted one experimental session, requiring approximately 25 minutes. No more than two sessions per day per subject were run, separated by at least 30 min. rest.

Participants

Three observers participated, two of the authors (BS, LA) and a paid naive observer (DA).

RESULTS

Random visual textures

The three subjects' mean contrast settings of the random texture test patch (ordinates) are plotted against the luminance contrasts of the surround of the standard patch (abscissas) in Figure 4. The open and filled circles correspond to luminance contrasts of the surround of the test patch of 0 and 1, respectively. The horizontal solid line represents the luminance contrast of the standard patch. The unconnected data points represent the stimulus in which the luminance contrast of the standard patch equaled that of its surround. For this point there was no contour between the standard patch and surround, so that the display was a continuous 5.6 deg patch of random noise. The apparent contrast of the standard patch did not decrease monotonically as the luminance contrast of its surround increased. Instead, for both contrasts of the surround of the test patch (0 or 1) the sharp suppression occurred at the point where the luminance contrast of the surround became higher than that of the test patch. At that point the curves separate into two more or less flat horizontal sections separated by a vertical shift.

The amount of suppression of apparent contrast can be described as the distance of the data point from the solid horizontal line representing the physical contrast of the standard patch. The upward deviation when contrast of test surround equals 1 is the same suppression as the downward deviation which occurs when contrast of the test surround equals 0. This contrast suppression occurred at different parts of abscissas for the two surround contrasts of the test patch. When the luminance contrast of the surround of the test patch was 0 (open circles) the suppression occurred when the standard (or comparison) patch luminance contrast was lower than that of its surround (the right side of the curve). When the luminance contrast of the test patch surround was 1 (filled circles) the suppression occurred when the standard patch luminance contrast was higher than the luminance contrast of its surround (the left side of the curve).

Even though we did not observe enhancement effect, these results support Ejima's & Takahashi's (1985) finding about the importance of the relative relationship between the luminance contrast of the central patch and èits surround. Contrast suppression occurred whenever the luminance contrast of the central patch was lower than the luminance contrast of its surround. Under those conditions the luminances of central patch elements fall within the range of the luminances of the surround's elements.

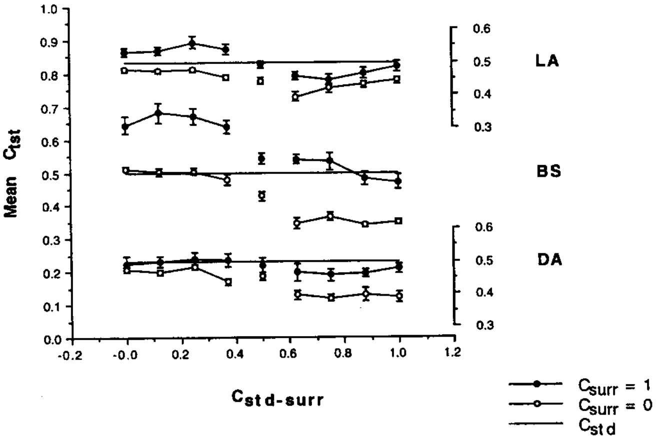
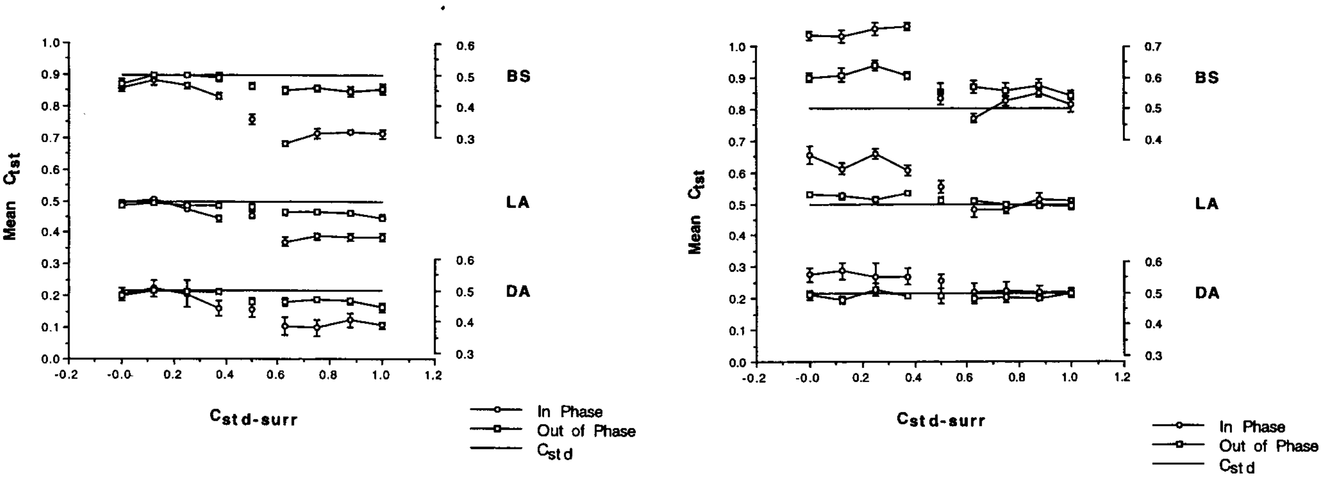


Figure 4. Data from three observers for the random texture patterns. Mean log contrasts of the test patch (ordinate) are plotted against the luminance contrasts of the surround of the standard patch (abscissa). Open circles: luminance contrast of the test surround = 0. Filled circles: luminance contrast of the test surround = 1. Horizontal solid line: physical contrast of the standard patch. Error bars are ±1 s.e.

Square-wave patterns

The three subjects' mean log contrast settings of the square wave test patches (ordinates) are plotted against the luminance contrasts of the surround of the standard patch (abscissas) in Figure 5. In Figure 5a the luminance contrast of the surround of the test patch was 0 and in Figure 5b it was 1. Circles and squares in each panel are for in-phase and out-of-phase displays, respectively. The horizontal solid line represents the luminance contrast of the standard patch. The unconnected data points represent the stimulus in which the luminance contrast of the standard patch equaled that of its surround. For in-phase patterns there was no contour between the standard patch and surround at this point, so that the display was a continuous 5.6 deg square-wave grating. For out-of-phase displays a subjective contour was formed by the terminations of the bars of the patch and surround, but the luminances were equal.

As with the random textures, the most prominent suppression of apparent contrast was restricted to a specific relationship between the luminance contrasts of the central patch and the surround. Furthermore, the suppression was dependent on the relative phase of the patch and background gratings. The greatest suppression was for in-phase patterns with the luminance



a. Luminance contrast of the test surround = 0.

b. Luminance contrast of the test surround = 1.

Figure 5. Data from three observers for the square-wave patterns. Mean log contrasts of the test patch (ordinate) are plotted against the luminance contrasts of the surround of the standard patch (abscissa). Circles: in-phase gratings. Squares: out-of-phase gratings. Horizontal solid line: physical contrast of the standard patch. Error bars are ±1 s.e.

contrast of the surround greater than that of the central patch (i.e. within the luminance range that supports the transparency interpretation). Suppression of apparent contrast was considerably smaller for 180 deg out-of-phase patterns and for in-phase patterns when the luminance contrast of the surround was less than that of the central patch. Both the pattern-specific and pattern-non-specific suppression effects were rather small compared to those reported by previous investigators.

Cannon & Fullenkamp (1991) found maximum suppressions of 0.4 log units for two subjects and 0.25 for a third, with test patch and background luminance contrasts of 0.25 and 0.50, respectively. In our data the maximum suppressions were 0.25 log units for BS and 0.12 for LA and DA, with test patch and background luminance contrasts of 0.50 and 1.00, respectively.

Perhaps the most interesting confirmation of our predictions is the almost perfect overlap of the curves for out-of phase patterns and patterns in-phase but outside of the luminance range that supports transparency.

Cannon & Fullenkamp (1991) reported that the apparent contrast of the test patch decreased monotonically as the physical contrast of the surround increased from zero. This applied even when the physical contrast of the surround was identical to that of the test: the apparent contrast of a grating decreased as its area increased. Two of our subjects (LA, DA) did not show that effect (Figure 5a and 5b, circles).

DISCUSSION

Suppression of apparent contrast was dependent upon the relative phases of the standard patch and background pattern only when the physical contrast of the standard was less than that of the background (right side of Figure 5a, left side of Figure 5b). Under these conditions the in-phase display had the appearance of one large, continuous grating with a superimposed transparent layer over the region of the test patch. When the physical contrast of the standard patch was greater than that of the background, there was no such transparent layer appearance, and phase had almost no effect (left side of Figure 5a, right side of Figure 5b).

The properties of this suppression of apparent contrast cannot be explained by simple inhibition among pattern-specific detector mechanisms. It does not seem to be a smoothly increasing function of background luminance contrast, but rather better represented by two separate horizontal sections of the curves for in-phase patterns in Figure 5a and Figure 5b. One might argue that the data are produced by pattern-specific mechanisms which generate a limited amount of inhibition only when stimulated above a threshold, but this would require that the threshold just happen to always coincide with the contrast of the standard patch, for all of our patterns. This seems unlikely to us.

We propose that two mechanisms contribute to the contrast-contrast effects in our data. Both have properties inconsistent with traditional conceptions of inhibition among pattern-specific detector mechanisms. One is restricted only to luminance relations that are consistent with the center's appearance as a transparent veiling luminance lying on continuous background texture. This mechanism requires that the luminances of the central patch lie within the luminance range of the inducing surrounding pattern and that the two patterns have the same spatial frequency, orientation, and phase. The second mechanism is not pattern specific. It is an untuned, global mechanism that can account for the suppression of apparent contrast in out-of-phase patterns and the brightness differences between equal-luminance uniform gray patches embedded in surrounds with high and low luminance contrasts. Furthermore, we suggest that the same mechanism is responsible for the contrast suppression observed for the in-phase patterns when the luminance relationships between elements of the test patch and the surround texture are not compatible with the perception of transparency.

Even though the first of our proposed mechanisms is restricted to spatial and luminance relations that support perceptual interpretation that involves transparency, it does not necessarily involve higher-order cognitive mechanisms. We have also demonstrated the dependence of other, clearly low-level phenomena on the same luminance relationships between figural and inducing background elements. Figure 6a shows the "grating induction" phenomenon (McCourt, 1982). The vertical stripes are uniform in luminance, but they appear to have a faint periodic pattern. Like contrast contrast, the phenomenon occurs only under restricted relations of luminance ranges, an effect not predicted by simple inhibitory interactions. This can be seen in Figure 6b: the induced pattern is prominent only when the luminance of the vertical stripes lies between the luminances of the horizontal background stripes.

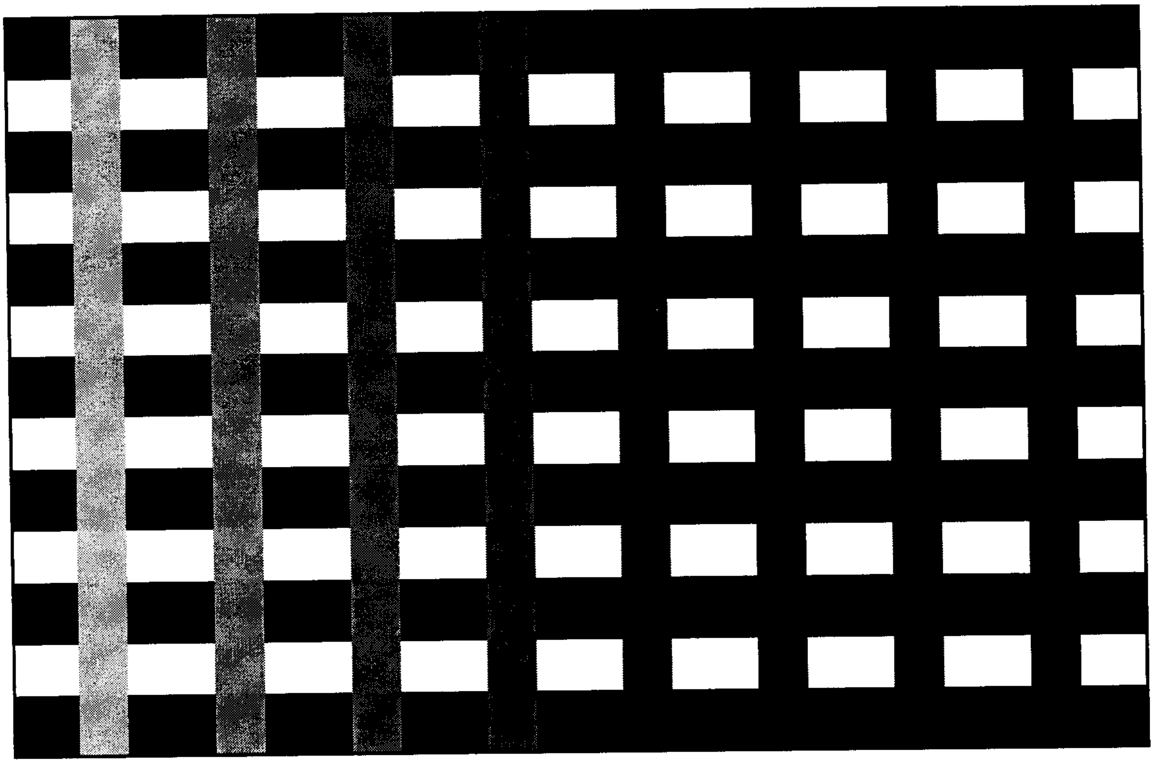


Figure 6. a. Grating induction: when uniform strips (vertical) are placed within a grating, a grating in opposite phase is perceived within the uniform strips.

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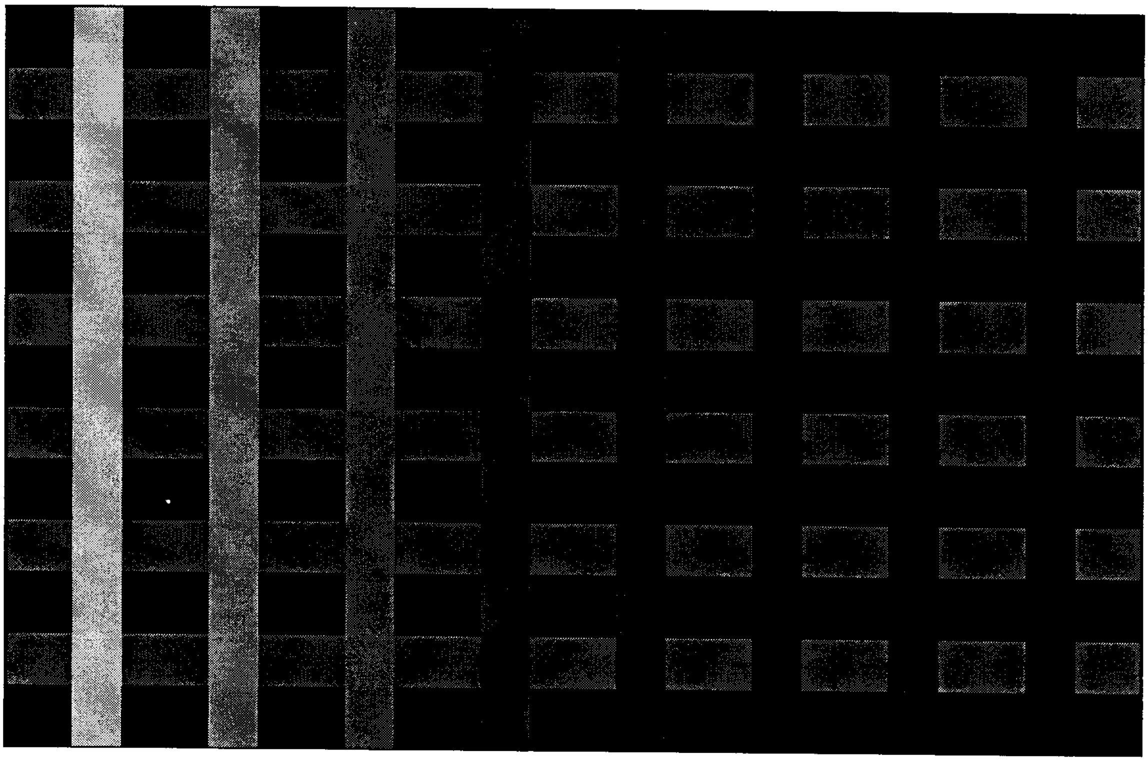

Figure 6. b. Luminance range constraint on grating induction: the induced grating pattern is prominent only when the luminance of the vertical strips lies within the luminance range of the horizontal stripes (i.e., four vertical stripes on the right hand side of the display).

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