

Visual aftereffect of texture density contingent on color of frame

FRANK H. DURGIN

Swarthmore College, Swarthmore, Pennsylvania

An aftereffect of perceived texture density contingent on the color of a surrounding region is reported. In a series of experiments, participants were adapted, with fixation, to stimuli in which the relative density of two achromatic texture regions was perfectly correlated with the color presented in a surrounding region. Following adaptation, the perceived relative density of the two regions was contingent on the color of the surrounding region or of the texture elements themselves. For example, if high density on the left was correlated with a blue surround during adaptation (and high density on the right with a yellow surround), then in order for the left and right textures to appear equal in the assessment phase, denser texture was required on the left in the presence of a blue surround (and denser texture on the right in the context of a yellow surround). Contingent aftereffects were found (1) with black-and-white scatter-dot textures, (2) with luminance-balanced textures, and (3) when the texture elements, rather than the surrounds, were colored during assessment. Effect size was decreased when the elements themselves were colored, but also when spatial subportions of the surround were used for the presentation of color. The effect may be mediated by retinal color spreading (Pöppel, 1986) and appears consistent with a local associative account of contingent aftereffects, such as Barlow's (1990) model of modifiable inhibition.

After adaptation to a dense texture localized in a specific region of the visual field, a visual aftereffect develops such that textures presented in that region will appear much less dense than when presented in another, non-adapted region (Anstis, 1974; Durgin & Proffitt, 1991). In the present paper I show that this aftereffect of texture density (not to be confused with spatial frequency) can be made contingent on color information presented in a spatially distinct (and otherwise untextured) region of the display. Previously, aftereffects both of motion (Potts & Harris, 1975) and of color (Siegel, Allan, & Eissenberg, 1992) have been made contingent on information presented in a surrounding region or *frame* (color and texture in the former case and lightness in the latter). However, no frame-contingent aftereffects have been reported in which the apparent spatial distribution of luminance contrast is altered. Thus, the present study represents a unique demonstration of an aftereffect of spatial pattern contingent on information in the surround.

It is often possible to make the perceptual distortion of one visual dimension contingent on the presence of another quite different dimension. For example, McCollough

(1965) found that after extended adaptation to orange and black vertical gratings and blue and black horizontal gratings, achromatic gratings would appear bluish when vertical and orangish when horizontal. The McCollough effect (ME) is probably the best known, but there are dozens of other contingent aftereffects (CAEs). In each case, the fundamental paradigm for inducing a CAE can be described as adaptation to two different values of one sensory dimension (e.g., orange and blue) in the presence of two different values of another (e.g., horizontal or vertical gratings) with a (usually 1.0) correlation between particular values across dimensions. A contingent aftereffect is evidenced if, as a consequence of the adaptation, the perception of one dimension is differentially biased by the presence of the specific values of the other.

McCollough (1965) proposed that her effect was due to color adaptation of edge detectors such as those recently discovered in the primary visual cortex by Hubel and Wiesel (1962). Subsequent theoretical accounts have varied considerably, with the strongest contenders being those that postulate adaptation of single units with dual sensitivities (e.g., the color- and orientation-sensitive neural units identified by Michael, 1978) and those that postulate modified associations (see Harris, 1980, for a review). Associative accounts have varied from classical conditioning models (see, e.g., Murch, 1976; Siegel et al., 1992) to specific neuronlike models of modified inhibitory interaction between simultaneously activated units (see, e.g., Barlow & Földiák, 1989). Although a frame-contingent aftereffect would seem to suggest a level of global interaction more like classical conditioning than local adaptation, in the context of what is known about the probable locus of other contingent aftereffects and what is known about lateral color

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spreading in the retina (Pöppel, 1986), I will argue that a more moderate associative account (i.e., that of Barlow, 1990) is a strong candidate for explanation of the present findings. Note that Barlow's interunit inhibition account is consistent with an account postulating the adaptation (not to be confused with neuronal fatigue!) of neural units, because adaptation itself has also been argued to involve inter-unit inhibition (e.g., Blakemore, Carpenter, & Georgeson, 1970; Tolhurst, 1972).

One goal of the present experiment was to develop a better understanding of the adaptability of texture density perception. I chose to use color as the associated visual dimension because of the clear evidence of interactions between color and form information in the McCollough effect. I chose to use a colored frame surrounding the textures rather than coloring the textures themselves because this method eliminates the trivial explanation that the resulting aftereffects of texture are due to the fatigue or adaptation of color-specific mechanisms that detect the textures. It is not necessary to postulate long-range color-form interactions, however, because of evidence of retinal color spreading (Pöppel, 1986). Retinal color spreading suggests that color information from one region, though not perceptually experienced, may be precortically represented over large retinal areas not exposed to color. Note that even in this case the separation of texture and color information remains intact because the texture information need not modulate the color, and the color information, itself, need not transmit form (i.e., spatial texture) information.¹

To place the present experiment within the context of the larger literature concerning contingent adaptation, I provide here an overview of many of the known varieties of contingent visual adaptation and evidence relevant to their locus in visual processing. In addition, a chart summarizing the varieties of contingent visual aftereffects is shown in Figure 1, and Table 1 provides citations to reports

of these various effects and includes a number of contingent aftereffects found in other modalities as well. For a more extensive review of much of the recent literature on the McCollough effect, in particular, see Humphrey (in press).

Varieties of Contingent Visual Aftereffects

The many visual dimensions that have been shown to be susceptible to contingent adaptation can be divided, somewhat arbitrarily, into four broad classes: Color, motion, time (visual duration), and spatial pattern. I will not discuss contingent aftereffects concerning perceived duration, because relatively little is known about them. Contingent color aftereffects, such as the ME, have been studied most extensively and have provided the most detailed evidence about probable sites and mechanisms for contingent adaptation. On the other hand, contingent aftereffects of motion probably demonstrate the broadest variety of associateable dimensions, as can be seen in Figure 1. I will discuss each of these classes in turn before discussing CAEs of spatial pattern.

CAEs of color. Color aftereffects have been made contingent on several kinds of spatial pattern information (see Harris, 1980, for review) and on motion (Hepler, 1968; Stromeyer & Mansfield, 1970). There is some controversy about the variety of stimuli that may be sufficient for inducing contingent colored aftereffects. For example, though Allan, Siegel, Collins, and MacQueen (1989) seemed to have demonstrated a text-contingent color aftereffect, it has subsequently been shown to be reducible to local retinotopic adaptation (Humphrey, Skowbo, Symons, Herbert, & Grant, 1994). Similarly, it has been shown that color aftereffects contingent on locally orthogonal pairs of patterns from the Lie transformation group (e.g., a pattern of concentric circles and a pattern of radiating lines are one pair of locally orthogonal patterns; Emerson, Humphrey, & Dodwell, 1985; Humphrey, Dodwell, & Emerson, 1985)

Contingently Adapted Dimension

Eliciting Dimension	color	orientation	size	motion	brightness	density	duration
color	✓	✓	✓	✓			
orientation	✓	■	■	✓	✓	✓	
spatial frequency	✓	■	■	✓			
motion	✓			■			
intensity				✓	■		
direction of gaze				✓			
binocular disparity				✓			
temporal order					✓	✓	✓
color of surround	■	■	■	■	■	■	■
spatial pattern of surround				✓		✓	
brightness of surround	✓						

Figure 1. Varieties of known visual contingent aftereffects are indicated by checkmarks. Columns refer to adapted dimension; rows indicate dimension on which aftereffect is contingent. References documenting these contingent aftereffects may be found in Table 1.

Table 1
Demonstrated Varieties of Contingent Aftereffect

Visual Contingent Aftereffects	
Color × orientation	McCollough, 1965
Orientation × color	Held & Shattuck, 1971
Color × spatial frequency	Harris, 1970; Leppman, 1972; Breitmeyer & Cooper, 1972; Lovegrove & Over, 1972; Stromeyer, 1972
Spatial frequency × color	Virsu & Haapasalo, 1973
Color × motion	Hepler, 1968; Stromeyer & Mansfield, 1970
Motion × color	Favreau, Emerson, & Corballis, 1972; Mayhew & Anstis, 1972
Brightness × orientation	Over, Broerse, Crassini, & Lovegrove, 1974; Allan & Tirimacco, 1987; Mikaelian, Linton, & Phillips, 1990; see also Mayhew & Anstis, 1972
Motion × orientation	Mayhew & Anstis, 1972
Motion × spatial frequency	Mayhew & Anstis, 1972; Walker, 1972
Motion × intensity	Mayhew & Anstis, 1972
Motion × direction of gaze	Mayhew, 1973
Motion × binocular disparity	Anstis & Harris, 1974
Visual duration × temporal order	Walker, Irion, & Gordon, 1981
Texture density × orientation	Durgin, 1995a; Durgin & Proffitt, in press
Texture density × temporal order	Durgin & Hammer, 1994
Texture brightness × temporal order	Durgin, 1995a; Durgin & Hammer, 1995
Color × brightness of surround	Siegel, Allan, & Eissenberg, 1992
Motion × color of surround	Potts & Harris, 1975
Motion × texture of surround	Potts & Harris, 1975
Texture density × color of surround	Durgin, this article
Auditory Contingent Aftereffects	
Duration × pitch	Walker & Irion, 1979
Duration × temporal order	Allan, 1984; Walker & Irion, 1979
Pitch loudness × context	Marks, 1992
Haptic Contingent Aftereffects	
Size × hand position	Walker & Shea, 1974; Walker, 1978
Size × hand orientation	Walker, 1977

Note—First dimension listed is the adapted dimension. This table is not necessarily exhaustive. Some existing contingent aftereffects may have been inadvertently left unrepresented; others have been left out because controversial or unreplicated.

also appear to be due to quite local, retinotopic form adaptation (Broerse & O'Shea, 1995; McCollough, 1994). Although there is controversy surrounding the possibility of nonretinotopic adaptation to certain other fairly simple forms (Broerse & Grimbeek, 1994; Humphrey, Herbert, Symons, & Kara, 1994; Siegel, Allan, & Eissenberg, 1992, 1994), most investigators support the view that the effects are primarily due to local form (e.g., local orientation and spatial frequency).

This conclusion is consistent with other evidence that the site of the ME appears to be quite early in visual processing. The effects are retinotopic and monocular (McCollough, 1965; Murch, 1972; but, cf. MacKay & MacKay, 1975; Savoy, 1984; and Vidyasagar, 1976, for evidence of dichoptic and binocular effects) and are specific to retinal orientation (Bedford & Reinke, 1993; Ellis, 1976), retinal size (Harris, 1970), and retinal color (i.e., wavelength, rather than perceived color; Thompson & Latchford, 1986). There is also evidence that conscious perceptual discriminability of the form stimuli is not critical to the effect (Humphrey, Gurnsey, & Fekete, 1991; Thompson & Travis, 1989). Indeed, the effect can be generated in patients who have severe cortical impairments of form and orientation perception with a sparing of area V1 (Humphrey, Goodale,

Corbetta, & Aglioti, 1995; Humphrey, Goodale, & Gurnsey, 1991), suggesting a locus in primary visual cortex (i.e., where McCollough, 1965, first proposed). It remains possible, of course, that contingent color distortions may be generated at several stages of perceptual processing, but the strongest, most characteristic effects probably have an early locus (see Humphrey, in press; Skowbo, 1984; Stromeyer, 1978, for excellent reviews).

In nearly all the demonstrations of CAEs of color, the pattern or motion information that serves as a cue is presented in the same location as the color. However, this spatial contingency between color and form is not strictly necessary. For example, stronger MEs are found when a region much larger than the grating is filled with the inducing color during adaptation (Siegel, Allan, Roberts, & Eissenberg, 1990). Moreover, an aftereffect of color contingent on the lightness of the surrounding region has recently been reported by Siegel et al. (1992). They presented a homogeneous red square within a black frame and a homogeneous green square within a white frame during adaptation (or vice versa). During the posttest, they found that the perceived color of a grating was contingently biased by the lightness of the surrounding frame. It must be stressed that frame-contingent aftereffects might still be

due the local adaptation of particular neural units that might be simultaneously sensitive to more than one visual dimension, both because they may be induced primarily at edges (of different contrast polarities) and because there is a great deal of lateral interaction in the visual system.²

CAEs of motion. In addition to CAEs of color, contingent aftereffects have been demonstrated for a large number of pairs of visual properties, as illustrated in Figure 1. Consider the variety of contingent aftereffects of motion: By correlating distinct directions of motion with distinct stimulus colors during adaptation, Favreau, Emerson, and Corballis (1972) and Mayhew and Anstis (1972) showed that a motion aftereffect (MAE) could be made contingent on the color of the test stimulus. Walker (1972) and Mayhew and Anstis (1972) demonstrated MAEs contingent on the texture or pattern of the test stimulus. Anstis and Harris (1974) demonstrated MAEs contingent on the binocular disparity or depth of the test stimulus, after an appropriate adaptation pairing of motion and disparity. Potts and Harris (1975) demonstrated that the direction of centrally induced MAEs could be made contingent on the pattern or color of stimuli presented in a static surround (see also Sharpe, Harris, Fach, & Braun, 1991). Mayhew (1973) has made the direction of motion of an adapting stimulus contingent on whether the observer was looking to the left or right and produced MAEs that were contingent on where the observer looked. In short, MAEs can be made contingent on simple visual information such as the dimensions of color, orientation, spatial frequency, and disparity information, as well as on some more surprising kinds of cues such as direction of gaze and pattern or color information presented in a surrounding region.

Color-contingent aftereffects of motion are commonly attributed to chromatic motion channels (see, e.g., Favreau, 1981). In their investigations of MAEs contingent on the color of the surround, Sharpe et al. (1991) argued that these were due to the lateral spreading of color information, such as that documented by Pöppel (1986), which in turn activated chromatic motion channels. Pöppel had shown that color aftereffects induced by a colored frame (see Anstis, Rogers, & Henry, 1978) depended on lateral color interaction in the retina. Sharpe et al. did not attempt to explain the MAE contingent on *spatial information* in the frame, which was also reported by Potts and Harris (1975). However, Anstis and Reinhardt-Rutland (1976) have shown that motion aftereffects can be produced by induced motion (from a surround) and can themselves induce motion. If a component of motion perception is *relative* motion perception (i.e., the motion of a center relative to its surround), then it is possible to conclude that the frame-pattern contingent motion aftereffect is due to local interactions between motion and pattern information with the lateral interactions arising, in this case, within the nature of motion processing itself—that is, from the comparison of the relative motion signals of the inner and outer regions.

CAEs of spatial pattern. Contingent aftereffects of spatial pattern have generally received the least amount of explicit attention. This is unfortunate, given the impor-

ance of spatial vision. Color-contingent aftereffects of orientation (Held & Shattuck, 1971) and spatial frequency (Virsu & Haapasalo, 1973) have both been demonstrated. However, because pattern information depends on wavelength-specific receptors, color-contingent spatial pattern adaptation may appear to be a fairly trivial consequence of overworking a set of pattern mechanisms with biased color inputs (see, e.g., Michael, 1978). If there are subpopulations of oriented spatial-frequency detector mechanisms that are more sensitive to one color than to another due to an incidental biasing of their retinal (cone) inputs, then exposure to gratings of a certain spatial frequency, orientation, and color should produce color-contingent distortions of this type. The present paper is concerned with a contingent aftereffect of spatial pattern in which this kind of explanation appears less probable because of the physical separation of color and pattern information during adaptation and assessment.

Contingent aftereffects of texture density have not previously been reported (but see Durgin, 1995a; Durgin & Hammer, 1994), nor have there been previous reports of aftereffects of spatial pattern that are contingent on information in a surround. Because texture density adaptation has only recently been distinguished from spatial frequency adaptation (Durgin & Proffitt, 1991), the present investigations were designed to determine (1) whether a color-contingent aftereffect of density could be generated, and moreover (2) whether it could be generated when the color information itself was unpatterned, and the texture information uncolored. As described above, such a finding would tend to favor an associative neural account of adaptation, though the particular associative account I will argue for is more akin to an information processing account than to a classical conditioning account.

Plasticity in Spatial Vision

Contingent aftereffects and long-term simple aftereffects have been construed as a tuning or structural change in the visual system by a number of investigators (e.g., Anstis, 1975; Barlow, 1990; Dodwell & Humphrey, 1990, 1993; Wolfe, 1990; Wolfe & O'Connell, 1986). Karni and Sagi (1991, 1993) have investigated plasticity in early spatial vision using a very different approach. They have demonstrated what they construe as the development of texture-filtering mechanisms that are retinotopic and texture specific. In their experiments, the participants' primary task is to detect a target among distracters. Typically the target is a texture composed of a few oriented bars, and the background texture is composed of bars oriented in another direction. They measured changes in the length of delay between stimulus and mask (SOA) at which participants' detection rate reached a criterion. The principal finding of this research was that participants showed long-term, lasting improvement that seemed to be consolidated during sleep. The learning was clearly visual in nature, because it was monocular, retinotopic, and was also specific to the orientation used as the background texture, but not the foreground (target) texture. For this reason, the learning seems to resemble the development of a visual "filtering

out” of the background texture in the service of preattentive texture boundary detection.

Aftereffects of Texture Density

Another kind of “filtering out” of texture is texture density adaptation (Durgin, 1995b; Durgin & Proffitt, 1991). Texture density refers to the number of texture elements per unit of visual area, or the (non-Fourier) frequency of elements in a visual texture. Texture density is typically confounded with luminance (when changes in the number of texture elements change the luminance of the texture) or with spatial frequency (when element size and element density covary). These confounds can be avoided, however, by the use of randomly scattered texture elements of uniform size that individually have the same average luminance as the background on which they are presented. The textures used by Durgin and Proffitt (1991) and in Experiments 2 and 4 of this paper are composed of such *luminance-balanced dots* (see Carlson, Moeller, & Anderson, 1984). Neither overall luminance nor the shape of the power spectrum of textures composed of such dots varies with density.

Durgin and Proffitt (1991) have shown that texture density (as distinct from texture magnification, studied by Anstis, 1974, and Walker, 1966) is subject to a visual aftereffect: Textures presented to a region of the visual field that has first been adapted to dense textures will appear markedly less dense than when presented to a nonadapted region. The paradigm used to measure this effect involved having participants compare the densities of two regions after adapting only one region to repeated presentations of dense textures. For example, if one gazes at the fixation mark of the upper panel of Figure 2, a region of the visual field to the right of the fixation mark will be exposed to a dense texture. If, after several seconds of such adaptation, one then gazes at the fixation mark of the lower panel, the right-hand texture will now appear less dense than the left (although it is the same image, mirror-reflected). Using textures controlling both luminance and spatial frequency, Durgin and Proffitt measured distortions on the order of a 50% reduction in perceived density in the adapted region.

In the present investigations, I have modified Durgin and Proffitt’s (1991) density adaptation procedure to introduce a contingency between (1) the relative density of textures presented in two comparison regions during adaptation (i.e., which of the two textures is denser) and (2) the color of the region surrounding the two textured regions. Instead of having participants adapt to patterns in which one region is always denser, the side on which the denser adapting texture appears varies randomly between trials, but is perfectly correlated with the color of the surrounding frame. As will be shown below, this manipulation does produce a density aftereffect contingent on color information presented in surrounding areas of the screen.

Four experiments are reported here. Experiment 1 is a demonstration of a frame-contingent density aftereffect using black-and-white textures. Experiment 2 replicates Experiment 1 while unconfounding luminance and density of the textures and luminance and chroma of the sur-

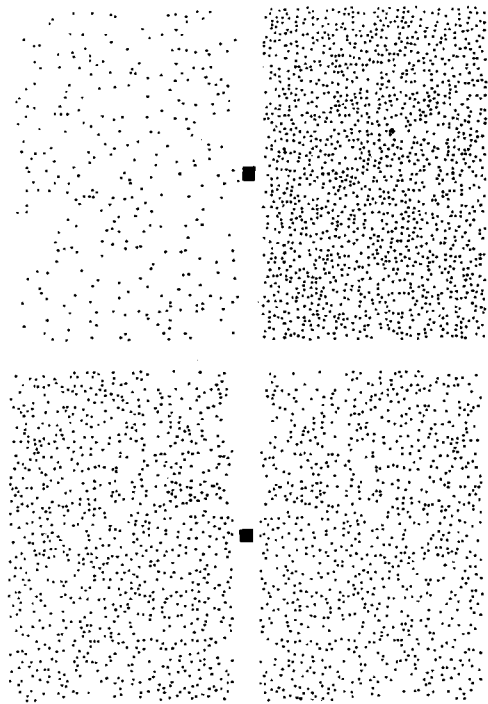


Figure 2. Demonstration of texture density aftereffect. After an adaptation to upper texture pair, in which the right field is denser, the left field of the lower texture pair will appear denser than the right. See text for details.

rounds. Experiment 3 demonstrates that the effect is not due to color contrast of the textured region and the surround. Experiments 4a and 4b show that different subportions of the surround are separately sufficient to produce the effect.

EXPERIMENT 1

The first experiment was a demonstration that the perceived relative density of texture in two regions can be made contingent on information specified in a frame surrounding the two regions. Black-and-white textures were presented within frames of yellow or light blue.³ Color of frame was correlated with the relative density in the two textured regions during adaptation. Density matches (points of subjective equality—PSE) were then measured in the context of each frame color. A contingent aftereffect would be evidenced if, in the presence of each frame color, there was a reduction of perceived density in the region that had been denser during adaptation in the presence of that frame color. Thus, a contingent aftereffect should appear as an inflated number of dots in the dense-adapted region at PSE, in compensation for the aftereffect.

Method

Participants. Twelve undergraduate students at the University of Virginia received course credit for their participation.

Display and Apparatus. The experiment was run on a Sun 3/60 workstation with an 8-bit RGB display monitor, 1,152 × 900 pixels, with a resolution of 40 pixels/cm. Participants were seated at a view-

ing distance of 85 cm (distance measured once the student was seated comfortably) so that each pixel subtended approximately 1 arc min of visual angle. The room was darkened.

Adaptation. During adaptation, participants were exposed to 500 brief (200-msec) flashes of adapting stimuli with an interstimulus interval (ISI) of approximately 800 msec. In their density aftereffect studies, Durgin and Proffitt (1991) adopted Wolfe and O'Connell's (1986) long-term tilt aftereffect methodology of repeated adaptation flashes. Durgin and Proffitt found strong density aftereffects even when these repeated adaptation flashes were brief. The flashes used here were especially brief to reduce unintentional eye movements during stimulus presentation, which might lead to color–texture retinal overlap. Brief test stimuli have been shown to produce larger aftereffects in studies of tilt aftereffects (Wolfe, 1984).

Two rectangular regions of the screen were used to present scattered-dot textures. The regions were 240×320 pixels ($\sim 4^\circ \times 5.33^\circ$) and were offset from the center of the display by 60 pixels ($\sim 1^\circ$) to the left and right. A small fixation mark was constantly present at the center of the display. In each adaptation flash, black-and-white scattered-dot textures were presented in the two regions, and the remainder of the display (apart from the fixation mark) turned either blue or yellow. The screen turned black, except for the fixation mark, during the ISI, so that the observer viewed the series of 500 briefly flashed adaptation stimuli at a rate of 1 per second with the fixation mark present throughout, and the entire adaptation session lasted about 8 min. Figure 3 depicts the two types of adaptation stimuli schematically.

The textures were made up of 2-pixel-square white dots scattered pseudorandomly (but constrained not to overlap or touch) against a black background. New random textures were generated for each presentation. One of the adapting textures was quite dense (56 dots/deg.² or 1,200 dots) and the other sparse (4.5 dots/deg.² or 96 dots). Readers acquainted with random dot textures may wish to note that even for the dense texture, only 6.25% of the pixels within the tex-

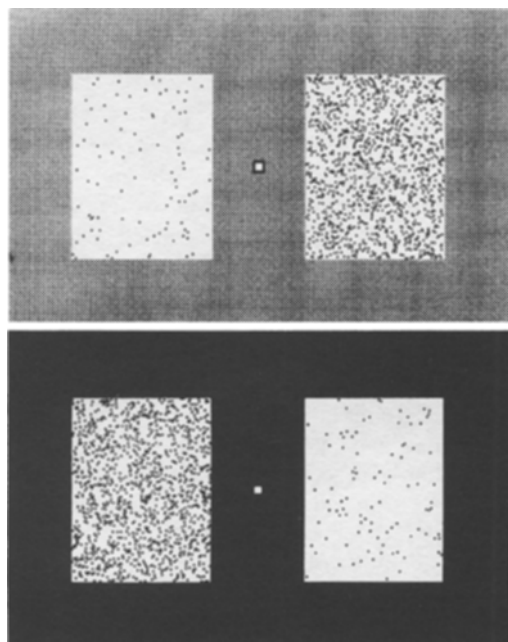


Figure 3. Schematic diagram of adaptation stimuli in which the texture density of the right and left regions are contingent on the color (indicated here by lightness) of the surround. Actual textures were white dots on black background for Experiment 1. Frame colors were light blue and yellow.

ured region were illuminated.⁴ The sparse adaptation texture was included to maintain similar levels of luminance contrast in the two regions. The left/right position of the denser texture was perfectly correlated with the color of the surrounding screen. For example, half the participants were presented with a denser texture in the left field whenever the screen was blue and a denser texture on the right whenever the screen was yellow. For the other participants, the pairing of color and denser texture position was reversed. Equal numbers of adapting trials (250) with each frame color were presented to each participant.

On the RGB monitor used, colors are specified by values of red (R), green (G), and blue (B) from 0 to 255. When $R = G = B$, the screen color is achromatic. $R = G = B = 0$ is black; $R = G = B = 255$, white. The yellow color was created with color index values of $R = G = 255$ and $B = 0$. The blue was a light blue defined as $R = G = 160$ and $B = 255$.

Measurement. The PSE were determined for each of three standard densities (400, 600, and 800 dots,⁵ or 18.7, 28.0, and 37.3 dots/deg.²) for textures presented in the two test regions in the presence of each of the two colored backgrounds. Participants made forced-choice decisions about which of two simultaneously flashed textures was denser. Measurement was accomplished by the modified staircase procedure described below.

Each staircase was a series of forced-choice trials (interleaved with trials from other concurrent staircases) in which the density of the left texture field remained fixed, and the right texture field varied from trial to trial according to the prior responses of the participant (although the distinction between variable and fixed field was not necessarily apparent to the participants). For each staircase, the density of the right field began as objectively equal to that of the left. On each subsequent trial, this value was altered by one *step* in the direction determined by the participant's response to the previous trial of that staircase. For example, if the participant chose the left field as denser on a given trial, the number of dots in the right field would be incremented by a predetermined number (step size) on the next trial of that staircase. A *turn* in a staircase is defined by different responses to successive trials of the staircase. The initial step size was 10% of the standard density. After the first turn, the step size was reduced to 7.5%, and after the second turn, to 5%, where it remained. Each staircase terminated at the eighth turn, and the values in the comparison field at the third through eighth turns were averaged to estimate the PSE. There were six staircases (3 standard densities \times 2 colors of background) interleaved at random according to a weighting scheme designed to make the termination of all staircases roughly synchronous. (In the pseudorandom selection process, each staircase was weighted by the square of the turns remaining in that staircase. A staircase with two turns remaining was therefore four times as likely to be selected as a staircase with only one turn remaining.) Test flashes, like adaptation flashes, lasted 200 msec. The screen was black except for the fixation mark following each test flash, and the next trial was presented only after the participant responded.

Although some fading or extinguishing of a contingent distortion might be expected to occur during the testing period, the primary purpose of the present experiment was to establish the presence of a distortion rather than to trace its time course. Nonetheless, it is possible to test for a change in distortion over time by comparing estimates of PSEs calculated from different points in the staircase.

Analysis. Because density aftereffects are best represented by differences of logarithms (i.e., a ratio; Durgin, 1995b), PSE scores were converted to differences between logarithms of the numbers of elements in the right and left fields at the point of subjective equality. That is, for each PSE a score was calculated as $\log(D_R) - \log(D_L)$, where D_R is the density in the right field and D_L the density in the left field at the PSE. Such a score is equivalent to the log of the ratio between the densities on the left and right fields. Because this transformation will be used for all the experiments described in this paper, a comment should be made about the rationale behind it.

Many psychophysical dimensions, including density (Burgess & Barlow, 1983) scale roughly logarithmically. What this means is that for a change in magnitude at one level of a scale to seem equivalent to a change in magnitude at another level of the same scale, the differences must be proportional (i.e., discriminable differences may be expressed as a Weber fraction). In logarithmic space, the difference between 10 and 11 is the same as the difference between 100 and 110. In a statistical analysis of psychophysical data, such differences ought to be equivalent. However, standard statistics are based on arithmetical, not proportional, differences, and would thus treat the difference between 110 and 100 as being much greater than that between 11 and 10. By performing a logarithmic transform, proportional differences become arithmetical differences, and the statistical analyses now work in an appropriate manner.⁶

If the logarithmic transformation still seems suspiciously "arbitrary" compared to an analysis of untransformed ratio scores, consider that if one analyzed the untransformed ratios, the results of one's statistical tests would depend on which portion of the ratio between two texture fields was expressed as the numerator: an analysis of the ratio of left-density/right-density is different from an analysis of the reciprocal of that expression. In contrast, because the logarithmic transform of the reciprocal of a ratio is equal to the negative of the logarithmic transform of the ratio itself [i.e., $\log(x/y) = -\log(y/x)$], the statistical tests on a logarithmic transform will come out identically whichever way the ratio is expressed. Thus, the use of logarithms for the present analyses is nonarbitrary for principled reasons. It is for these reasons that the scores subjected to analysis in these experiments are differences of logarithms [which are equivalent to logarithms of ratios, because: $\log(x) - \log(y) = \log(x/y)$]. Such scores can be expected to reflect only proportional distortions of density. For aid in comprehension of the numeric values thus obtained, I will refer to effect sizes in terms of the logarithm of a ratio, as in $\log(1.26)$, which would reflect a logarithm of a ratio that is equal to 1.26.

Procedure. Participants were tested individually. Each was instructed to use the fixation mark during both the adaptation and measurement phases. Participants were informed that they would first be asked to pay attention to the screen for several minutes without responding (the adaptation phase) and would then be required to judge the relative texture density of the two textured regions of the screen (measurement phase). After the presentation of all of the adaptation stimuli, the screen stayed blank until the participant pressed a button to go on to the measurement phase. No recovery period was used between adaptation and measurement because simple adaptation effects produced by the exposure to the stimuli could not account for any color-specific bias. During the measurement phase, participants indicated whether the left or right texture field appeared denser on each trial by pressing one of two mouse buttons. There were 85 measurement trials, on average, over a period of about 3 min.

Results

Mean PSEs for each of the six measurements are plotted in logarithmic space in Figure 4. Scores were collapsed according to whether the color of the background corresponded to that presented when the left or right field had dense texture during adaptation. As is evident from Figure 3, different directions of density distortions are associated with background color in the predicted manner.

A 3×2 (standard density \times frame color) repeated measures analysis of variance (ANOVA) was performed on the transformed scores. Note that frame color refers not to the absolute color of the frame (blue or yellow), but rather to the color associated with dense texture on a particular side for each participant. As anticipated, there was a highly reliable main effect of frame color [$F(1,11) = 22.76, p < .01$], indicating differential distortions of density contingent on

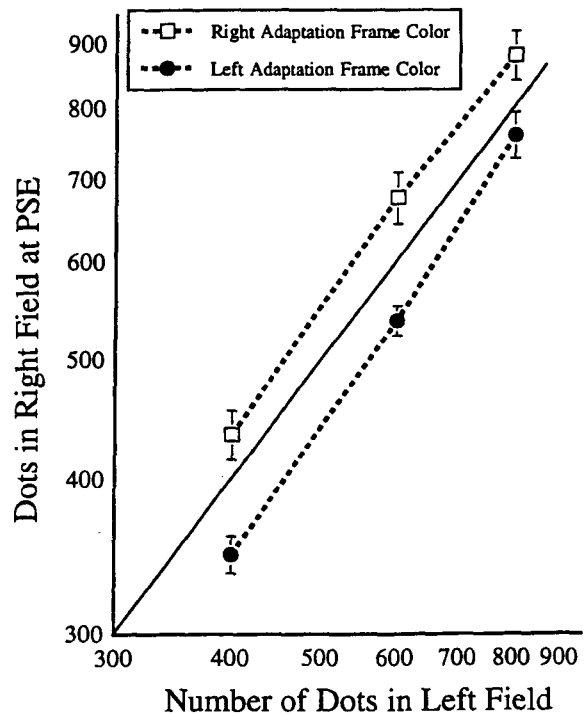


Figure 4. Results of Experiment 1. Points of subjective equality (PSE) between left and right texture fields are plotted for each frame color, illustrating contingent bias away from objective match. Error bars indicate standard error of the mean.

the color of the surround. As was also expected, there was no effect of standard density [$F(2,10) = 2.00, n.s.$].

When absolute background color (i.e., blue and yellow, independent of initial pairing of color and density) was used in the analysis, there were no reliable main effects, indicating that the particular colors used were not responsible for any intrinsic bias. Overall, these results show that density comparisons were reliably affected by the color of the surrounding frame according to density differences associated with that frame color during adaptation.

To test for evidence that the size of the contingent distortion changed during the time it took to measure it, a second analysis was carried out in which PSEs calculated from only the third and fourth turns of the individual staircases were compared with those from the seventh and eighth turns. For each of the three levels of density, a (difference-of-logarithms) frame-color contingent aftereffect score was computed at each of the two times. As expected, the contingent distortion score calculated from the later trials was reliably smaller than those calculated from the earlier trials [$F(1,11) = 5.20, p < .05$]. The mean contingent aftereffect scores at the two times were $\log(1.26)$ for Turns 3 and 4, and $\log(1.18)$ for Turns 7 and 8.

Discussion

A contingent aftereffect was indeed found: The apparent relative density of texture pairs is affected by contexts specified as colored frames when those contexts were pre-

viously correlated with relative density. Thus, it appears that the texture density aftereffect, like aftereffects of color (Siegel et al., 1992) and motion (Potts & Harris, 1975), can be made contingent on information that is provided at a different spatial location than the region to be judged.

There is evidence that the size of the effect measured by the staircase technique underestimates the initial effect size because the distortion declines during testing. It is well known that McCollough effect strength declines with exposure to test gratings (e.g., Skowbo, Gentry, Timney, & Morant, 1974). Durgin and Proffitt (1991) refreshed their simple adaptation effect before each trial to maintain its strength. This strategy was not employed here for fear that simple (noncontingent) adaptations for the denser side of the last-presented stimulus would add noise to the measurement of the contingent effect. Nonetheless, our principal goal of establishing the existence of an effect was successful.

Because black-and-white textures were used, and the relative luminance of the colored surrounds was not matched, both texture density and frame color were confounded with luminance in this demonstration. It is therefore theoretically possible that the present effect was due to a luminance aftereffect contingent on the luminance of the frame. Experiment 2 was conducted to demonstrate that the effect did not depend on luminance differences.

EXPERIMENT 2

To control for luminance of both the surrounds and the textures, Experiment 2 was a replication of Experiment 1 with several modifications. To decorrelate chroma and luminance in the frame, the colors used were five distinct brightnesses of roughly equiluminant shades of red and green. To decorrelate texture luminance and texture density, the texture elements used were balanced squares (after Carlson et al., 1984; Gilden, Bertenthal, & Othman, 1990), like those used by Durgin and Proffitt (1991).

Method

Participants. Twenty-three undergraduate students at the University of Virginia received course credit for their participation. Eighteen participated in the main experiment. An additional 5 participants were used to make color matches (see below) preliminary to the main experiment.

Display and Apparatus. The experimental apparatus was the same as that in Experiment 1, except that stimulus durations were increased to 500 msec to increase texture visibility, and participants were seated closer to the monitor (61 cm). As a result, all visual angles were increased by 50%.

Color selection. To produce five pairs of roughly equiluminant colors, a bright red ($R = 255, G = B = 0; 6.0 \text{ cd/m}^2$ —measured by UDT model 351 with photometric detector 265) and a darker red ($R = 231; 4.2 \text{ cd/m}^2$) were selected. Five preliminary observers used a minimum motion technique (Cavanagh, MacLeod, & Anstis, 1987) to find near-equiluminant greens for each red. The resulting bright and dark greens were averaged between participants, and the remaining brightnesses of red and green were interpolated using a linear scale of luminance derived from photometric measurement of the gray scale of the screen. In RGB specification, the brightest green was $G = 197 (R = B = 0)$, and the darkest was $G = 180$.

Adaptation. As before, participants were exposed to 500 flashes of adapting stimuli while fixating a small white square at the center of the display. There were 10 distinct frame colors: two chromas \times five levels of luminance. Chroma was perfectly correlated with the relative density of the two adapted regions. Luminance was uncorrelated with relative density and with chroma.

The texture elements were 4×4 pixel balanced squares composed of a 2×2 pixel white center and a black annulus 1 pixel wide. The background gray of the textures (2.8 cd/m^2) was selected so that the addition and subtraction of texture elements did not alter the photometrically assessed luminance of the display. The same background gray was used for the blank screen between stimuli. The adapting textures were the same in numerosity as in Experiment 1. The appearance of a dense balanced-dot texture is depicted in Figure 5.

Measurement. The PSE of density for textures presented in the two adapted regions was assessed for two levels of density (400 and 800 dots, or 8.3 and 16.6 dots/deg²), at two levels of frame luminance (the darkest and brightest used during adaptation) and at each of the two levels of frame color. These eight measurements were accomplished by the same staircase procedure as that described in Experiment 1.

Results and Discussion

As in Experiment 1, an aftereffect of texture density contingent on the color of the frame was found. Mean PSEs for each standard density and frame color are plotted in Figure 6. A $2 \times 2 \times 2$ (standard density \times frame luminance \times frame color) repeated measures ANOVA was performed on the log-transformed ratio scores. As is evident from the figure, there was a highly reliable main effect of frame color [$F(1,17) = 22.9, p < .01$], indicating differential distortions of density contingent on background color. There was no effect of standard density, in-

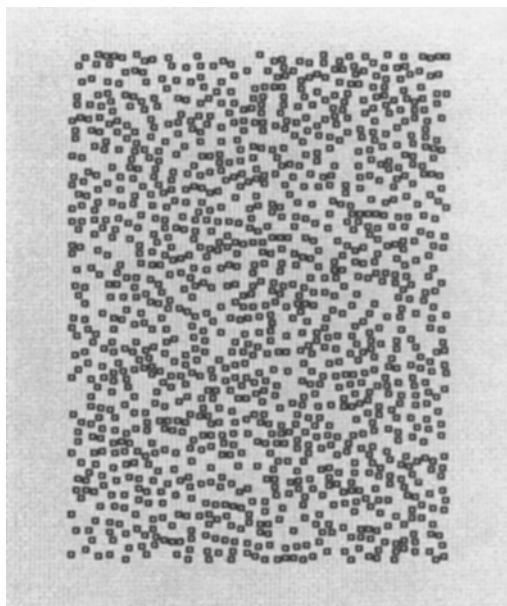


Figure 5. A diagram depicting a balanced dot texture, such as those used in Experiment 2. Actual luminance balance may not be maintained in this reproduction. If it were, the textured region would be equiluminant with the background gray and would be invisible at a large viewing distance.

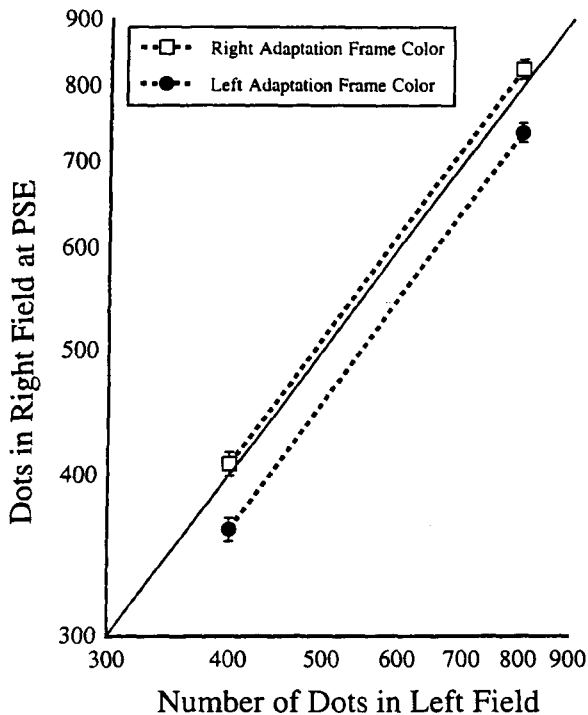


Figure 6. Results of Experiment 2. Points of subjective equality (PSE) between left and right texture fields are plotted for each frame color, illustrating contingent bias away from objective match. Error bars indicate standard error of the mean.

dicating that the distortion was proportional to density, as expected [$F(1,17) = 0.05$, n.s.]. Nor was there an effect of frame luminance [$F(1,17) = 0.59$, n.s.].

These results confirm that a texture density aftereffect can be made contingent on the color of the region surrounding the actual texture regions. The effect cannot be attributed to luminance adaptation, because the textures were all of the same space-average luminance. Nor is the effect contingent on the luminance of the surround, because surround luminance and surround chroma were decorrelated.

A second analysis, like that employed in Experiment 1, was carried out to test for evidence that the size of the contingent distortion changed during the time it took to measure it (PSEs calculated from only the third and fourth turns of the individual staircases were compared with those from the seventh and eighth turns). For each of the two levels of density and frame luminance, a (difference-of-logarithms) contingent aftereffect score was computed at each of the two times. Contrary to the results of Experiment 1, the contingent aftereffect scores calculated from the later trials did not differ reliably from those calculated from the earlier trials [$F(1,17) = 1.25$, n.s.].

EXPERIMENT 3

Is the basis of this color-contingent aftereffect a complementary color induced in the textures themselves by simultaneous color contrast with the surround? In their examinations of the motion aftereffect contingent on the

color of the surround, Sharpe et al. (1991) tried assessing the aftereffect with colors presented in the central location after adapting to a colored surround. This central location had been surrounded by color, but not colored during adaptation. It was possible that perceptual color contrast of the center with the surround formed the local basis for the contingent adaptation. If so, then adaptation to a red surround (which would normally produce a greenish appearance in the center) ought to be equivalent to adaptation with a green center. However, they found that the direction of the motion aftereffect during testing was appropriate to that of a red surround whether the color red was presented in the surround (as in adaptation) or in the center. Such a finding rules out an explanation for the lateral effects by means of simultaneous color contrast.

The present experiment serves a similar purpose. In Experiment 3, adaptation proceeded much as in Experiment 1 (except that the equiluminant greens and reds of Experiment 2 were used for the surround). However, during testing, the texture elements themselves appeared in color and the surrounding screen remained black. If simultaneous color contrast was mediating the laterally effective contingent distortions of the previous experiments, then red dots ought to have the same effect as a green frame rather than that of a red frame. In fact, red dots during testing will be shown to work much as does a red frame.

Method

Participants. Twenty-two undergraduate students at the University of Virginia received course credit for their participation. Two additional participants could not complete the experiment because of either equipment failure or failure to follow instructions.

Display and Apparatus. The experimental apparatus was the same as in the previous experiments. Viewing distance (61 cm) and stimulus durations (500 msec) were like those in Experiment 2.

Adaptation. As before, participants were exposed to 500 flashes of adapting stimuli while fixating a small white square at the center of the display. There were 10 distinct frame colors: two chromas \times five levels of luminance as in Experiment 2.

The texture elements were 2×2 pixel squares presented against black background. The squares were white during adaptation, but were colored during the measurement phase. The adapting textures were the same in numerosity as those in Experiment 1.

Measurement. The PSE of density for textures presented in the two adapted regions was assessed for three levels of density (400, 600, and 800 dots, or 8.3, 12.4, and 16.6 dots/deg²) for each of the two possible colors of texture element. The elements were assigned the brightest of each of the two frame colors. These six measurements were accomplished by the same staircase procedure as that in Experiment 1.

Results and Discussion

As in Experiments 1 and 2, an aftereffect of texture density contingent on the color of the frame was found. One participant was dropped from further analysis because his data indicated a contingent distortion of more than 3 standard deviations in excess of the mean.⁷ A 3×2 (standard density \times dot color) repeated measures ANOVA was performed on the log-transformed ratio scores of the remaining 21 participants. As expected, there was a reliable main effect of dot color [$F(1,20) = 4.77$, $p < .05$], indicating differential distortions of density contingent on the color

of the dots textures presented. The effect was in the same direction as in the previous experiments and therefore opposite to the predictions of effects of simultaneous color contrast. However, the mean effect size in this experiment [$\log(1.047)$] is significantly smaller than the mean effect size [$\log(1.121)$] of Experiment 2 [$t(37) = 2.18, p < .05$]. (See also Figure 8, below.) The reduced strength of the effect might be due to the reduction in similarity between the adaptation and test stimuli. On the other hand, as suggested in the following experiments, it may simply result from the relatively small amount of color presented during testing.

EXPERIMENTS 4A AND 4B

In Experiments 1 and 2, the colored frame extended around each of the textured regions and filled both the border of the screen and the region between the two textures. In Experiments 4a and 4b, the procedure of Experiment 2 was repeated, but in each experiment a different subportion of the surround was used for color presentation. The two subportions used are depicted in Figure 7. In one case, the color is presented foveally but does not surround the textured regions; in the second case, the color is limited to a peripheral border. We might expect to find greater influence of the peripheral border on the grounds of surround-induced color induction. On the other hand, foveal registration of color itself is substantially greater, which might predict a predominant effect of foveally presented color.

Experiment 4a

To test the importance of the position of the colored region, the region that changed color was limited to a vertical rectangle between the two textured regions.

Method

Participants. Twelve undergraduate students at the University of Virginia received course credit for their participation.

Procedure and display. The experiment was identical to Experiment 2 except for the dimensions of the colored region during adaptation and testing: Instead of the entire region surrounding the texture portions, only a central vertical stripe, as illustrated in Figure 7, changed color. This stripe was 112×900 pixels. The rest of the screen remained gray.

Results

One participant's data indicated an abnormally strong contingent bias in the opposite direction from that predicted, and these data were removed from further analysis as anomalous.⁸ As anticipated, a $2 \times 2 \times 2$ (standard density \times stripe lightness \times stripe color) repeated measures ANOVA on the log-transformed ratio scores for the remaining participants revealed a main effect only of stripe color [$F(1,10) = 6.48, p < .05$]. The mean contingent aftereffect size is shown in Figure 8.

Experiment 4b

In Experiment 4b, only an outer border of the screen changed color. This condition more closely resembles

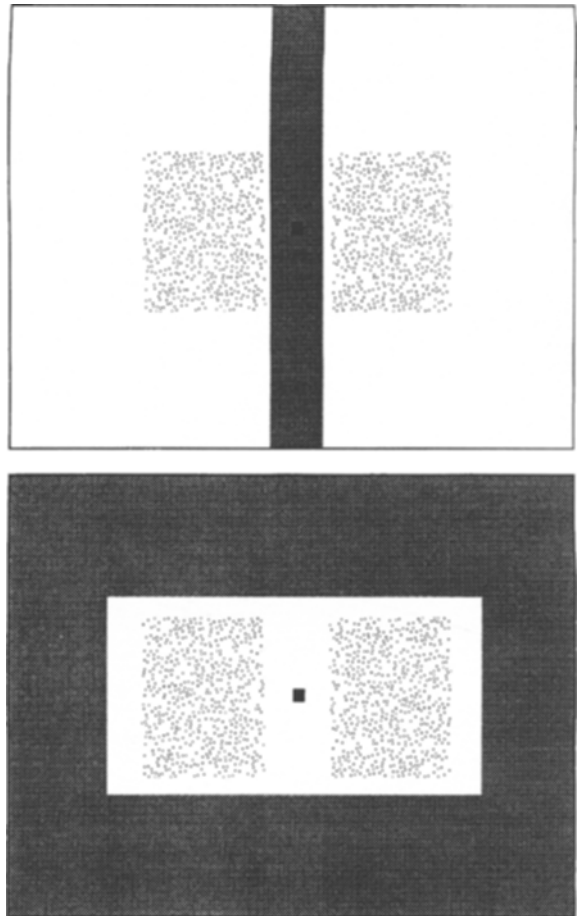


Figure 7. Diagrams (drawn to scale) indicating in gray the portion of the screen in which colors (red or green) were presented during adaptation for Experiments 4a (top) and 4b (bottom). Textures were balanced dot textures, and the uncolored portion of the screen was the same gray as the background of the textures.

prior frame effects (e.g., Potts & Harris, 1975; Siegel et al., 1992), in which frame information was not presented in the fovea.

Method

Participants. Seven students and staff at the University of Virginia were paid for their participation.

Procedure and display. The experiment was identical to Experiment 2 except for the dimensions of the colored region: As illustrated in Figure 7, only the outer border of the screen changed color during the experiment. The color border extended from the edge of the screen. It was 250 pixels thick at the top and bottom and 200 pixels wide at each side, with interior dimensions of 752×400 pixels. As a result, it was never closer than 1 cm to the textured regions, and never closer than 4.7° to the central fixation mark.

Results and Discussion

Once again, the PSE for density in the two regions was found to be contingent on the adapted relationship between relative texture density and the color of the frame. A $2 \times 2 \times 2$ (standard density \times border lightness \times bor-

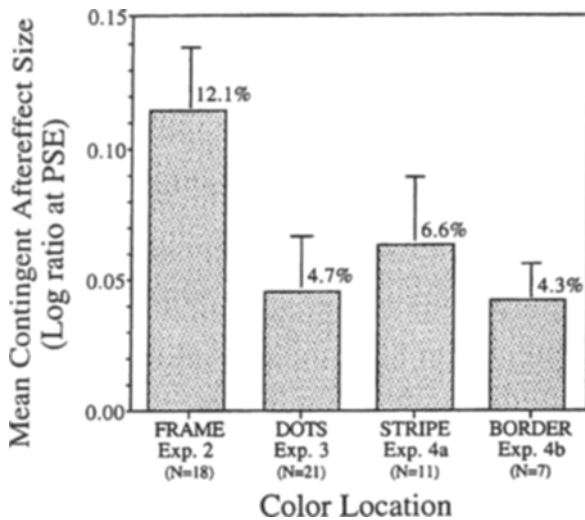


Figure 8. Mean contingent aftereffect sizes for Experiments 2, 3, 4a, and 4b. Error bars indicate standard error of the mean. Reported column values indicate mean scores of contingent density distortion expressed as a percentage of the standard density. (PSE, points of subjective equality.)

der color) repeated measures ANOVA performed on the log-transformed ratio scores indicated a reliable effect only of border color [$F(1,6) = 9.43, p < .05$]. Mean aftereffect sizes for each of Experiments 2, 3, 4a, and 4b are shown in Figure 8. Mean aftereffect sizes in Experiments 4a and 4b did not differ from each other [$t(16) = 0.645, n.s.$]. Overall, the mean effect size in Experiments 4a and 4b [$\log(1.057)$] was smaller than in Experiment 2 [$\log(1.121)$], $t(34) = 2.045, p < .05$, perhaps due to the quantitative decrease in color information.

It is difficult to compare the amount of (visually useful) color information presented in Experiments 4a and 4b, because although the stripe is only one seventh of the area of the border,⁹ it covers the fovea, where cones are densest, whereas the border is in the parafovea and periphery. However, the reduced size of the effect in Experiments 4a and 4b compared with that in Experiment 2 does suggest that the effective (transduceable) quantity of the associated inducing stimulus (color), rather than its retinal location, per se, is important to contingent adaptation. On the other hand, because there is a large difference in the physically present quantity of colored light, the similar size of the contingent aftereffects in Experiments 4a and 4b would seem to argue against the effect resulting from optical scatter of the colored light into the textured regions, for example.

The present findings are consistent with the idea that the small effect size found for Experiment 3, in which only the textures were colored during testing, may have been due, in part, to the quantity rather than the location of the color information. On the other hand, the quantity of color physically present in the test textures of Experiment 3 was always less than 8% of that present in Experiment 4a, yet the effect sizes are comparable, suggesting that color in-

formation that is spatially coincident with the texture may have some overall advantage.

GENERAL DISCUSSION

In the experiments reported here I have demonstrated that a distortion of perceived texture density can be made contingent on color information presented in a different spatial location. Thus, like aftereffects of color and motion, aftereffects of texture density can be made contingent on information presented in a surround.

Is it possible that these results are due to decisional response biases induced in the participants by the experimental situation? I have several reasons for doubting this. For one thing, the strength of this contingent aftereffect seems to vary in a sensible manner with the quantity of "cuing" information available. Because the "cue" is always well above threshold, the quantitative variation in the effect is more likely a measure of perceptual distortion rather than of a decisional response bias. Moreover, most participants express surprise at the direction of the aftereffect when they are debriefed, and state that they would have expected a distortion to go in the same direction as they were exposed to during adaptation. It might nonetheless be argued that a decisional response bias could arise from participants wishing to negatively influence the experimenter's expected outcome. However, although this explanation seems fairly improbable in itself, perhaps the clearest evidence against it is a recent finding that when auditory pitch is used as a cue in a similar experiment on texture density, a perceptual bias is found in the same direction as adaptation (Durgin & Proffitt, 1993; Durgin, 1995a). I conclude that the current effects are a result of biasing the perceptual system rather than some decision site external to perception.

Texture Perception

Density has long been conceived as a measure of texture strength or energy (see, e.g., Julesz, 1981), but a clear formalization of the coding of density itself has not yet been offered. Durgin (1995b) has suggested a spatial scale model of density aftereffects wherein distortions of density are the result of changed visual scaling. Such a scaling could be achieved, for example, by modulation of receptive field sizes (or the tuning of receptive fields). Durgin (1995b) argued that some such modification of the scale of visual analysis could account for density aftereffects and interactions between the perception of density and numerosity under conditions of density adaptation. Nonetheless, these ideas remain speculative.

Moreover, there are reasons to think that the density dimension is asymmetric in its direction of change. For example, though adaptation to dense texture will decrease the apparent density of a subsequently viewed texture, adaptation to a sparse texture has not been shown to increase the perceived density of a subsequent, somewhat denser, texture.¹⁰ This asymmetry is suggestive of an "intensity" (rather than a "size" or "extent") model of density repre-

sentation wherein any number of dots is dense relative to the absence of texture.

Intensity models of density might seem to suggest that perceived density might be based in luminance or luminance contrast information, because adaptation for these dimensions (relative to zero luminance or contrast) has a similar character. However, although Mulligan and MacLeod (1988) reported interactions between dot brightness and dot density for periodic stimuli, density adaptation for aperiodic stimuli has been experimentally differentiated from luminance and spatial frequency adaptation (Durgin & Proffitt, 1991) and from luminance contrast adaptation (Durgin & Hammer, 1994). It is possible that spatial scale can be construed as an intensive dimension that is stretched unidirectionally from its neutral rest state by texture processing.

Though the present article has offered no direct experimental evidence regarding the site of the present adaptation effects, a reasonable conjecture regarding the locus for adaptation is primary visual cortex. Such a site has been implicated both for plasticity in texture perception (e.g., Karni & Sagi, 1991) and for the McCollough effect. If this proves correct in further studies of the interaction of density with other visual dimensions, then it may shed some further light on the coding of texture density itself.

An Associative Account?

The frame-contingent modification of perception suggests a context-sensitive visual system. Such a description could easily be taken as supportive of a classical conditioning view of contingent aftereffects in which one stimulus is said to become associated with another (e.g., orientation with color) such that the former comes to evoke the perceptual response (color adaptation) to the latter. Such a view has been explicitly set forth a number of times with regard to the McCollough effect (see, e.g., Murch, 1976; Siegel et al., 1992). Similarly, a classical conditioning account of the current effect might speak of the colored frames as conditioned stimuli that produce conditioned responses in the perception of texture.

A difficulty with this way of speaking, however, is that it suggests that the associations are between global stimulus representations. Given the volume of evidence favoring an early (and retinotopically local) locus for the McCollough effect (e.g., Broerse & O'Shea, 1995; Humphrey, Goodale, & Gurnsey, 1991; Humphrey, Gurnsey, & Fekete, 1991; Humphrey, Herbert, Symons, & Kara, 1994; Humphrey, Skowbo, Symons, Herbert, & Grant, 1994), such a view seems unsatisfactory. Although a classical conditioning approach does not necessarily have to be identified with global stimulus representation, it does lend itself to the interpretation that the unit of association is the global stimulus. Indeed, although it is just as possible to imagine the argument made completely at a local neural level, current proponents of classical conditioning views have tended to analyze stimuli at the global level (e.g., text, as in Allan et al., 1989).

Conditioning theorists are not alone in looking to "global" stimuli as the basis for contingent adaptation. Bedford

(1995) has recently proposed an explicitly "cognitive" theory of the McCollough effect, which seems to suffer the same empirical difficulties. Arguing from principles of object constancy, she proposed that McCollough effects ought to be limited to pairs of forms that are projections of non-distorting transformations of the same object. Although this line of reasoning seems right-headed insofar as it supports concepts of recalibration and tuning that have been advanced by others (Dodwell & Humphrey, 1990; Held, 1980; Wolfe, 1990), its present formulation in terms of object constancy cannot be correct. A great deal of evidence from several laboratories supports the finding that forms that are locally orthogonal in orientation but globally completely unrelatable by the necessary kind of transformation do, nonetheless, produce (local) McCollough-like effects (e.g., Broerse & O'Shea, 1995; Dodwell & O'Shea, 1987; Dodwell & Humphrey, 1990; Emerson et al., 1985; McCollough, 1994; Yasuda, 1978).

Instead of suggesting that the present effect is due to associations or cognitive comparisons among global stimuli, it would appear safer to argue, as did Sharpe et al. (1991), that the lateral contingent interactions between visual dimensions may be partly mediated by lateral connections within those dimensions. For example, there is clear evidence of lateral spreading of color information at the retinal level. It is therefore easy to imagine that the effects observed here are due to purely local interactions between retinally spread color information and locally represented spatial pattern information. Thus, rather than an association between globally conceived visual stimuli, the modified associations may be quite local and need not be set in terms of global stimulus descriptions.

Sharpe et al. (1991) suggested that their results supported Favreau's (1981) account of color-contingent motion aftereffects in which these involve the adaptation of chromatic motion channels. However, a different perspective on this argument can be taken. Within the present context, it seems reasonable to believe that the retinal spreading of color information represents a pedestal of chromatic activity that does not, in itself, contribute to form discrimination. Thus, the neural unit (or assembly of units) that produces the frame-color-contingent density aftereffect must be sensitive to both color and form, but not necessarily color-specified form. Under this description, the simplest model of the contingent adaptation occurring here would probably be something very like Barlow's model (1990; Barlow & Földiák, 1989), involving inhibitory connections between pattern analyzers and color analyzers. That is, the unit of adaptation may be an (inhibitory) association between neural units, rather than adaptation of the units themselves.

Perceptual Adaptation and Contingency

Barlow's (1990; Barlow & Földiák, 1989) model represents a modern development of older ideas regarding adaptation (e.g., Gibson, 1933, 1937; Helson, 1964; see also Held, 1980). Helson argued that the *adaptation level* of a system represented a platform from which to evaluate other stimuli. Dodwell and Humphrey (1990) invoked Hel-

son's theory in their description of the McCollough effect as a kind of adaptation level between dimensions with the goal of error correction (Andrews, 1964). Barlow's formulation is more explicit with regard to mechanisms of adaptation and is less concerned with error correction than with efficient sensory representation: First, he proposes a simple mechanism of modifiable inhibitory connections (Barlow & Földiák, 1989) for producing simple and contingent adaptations. Second, he suggests that adaptation occurs to relationships between sensory dimensions as a way of screening out normal sensory correlations to make unusual relationships more evident.

Barlow's theory also differs from Dodwell and Humphrey's (1990) theory in that it is a theory of local interactions, whereas Dodwell and Humphrey argued for global influences (though the global claims can be dropped without much fuss in light of newer evidence, e.g., Humphrey, in press). But, most importantly, Barlow's is not an error-correction theory in quite the way that is emphasized by Dodwell and Humphrey. Error correction implies that there is a fixed state, deviations from which must be corrected. In Dodwell and Humphrey's model, this fixed state is represented by a zero correlation between the dimensions of form and color (stipulated to emerge from the long-term statistical properties of the sensory environment). In Barlow's theory, the adaptation to relationships is intended primarily to build into the visual system (or any other sensory system—Barlow & Földiák, 1989, discuss taste) a means of filtering out the *normal interactions* between dimensions for purposes of more efficient perceptual coding.

This difference appears to be important to Helson's (1964) own ideas regarding adaptation insofar as he distinguishes the concept of adaptation level from homeostasis. Homeostasis refers to internal corrections back to a fixed state, such as in temperature regulation in mammals. Helson specifically pointed out that adaptation levels were not fixed, but were labile. The perceptual adaptation of an organism to sensory contingencies, in this view, is very unlike homeostasis.

Barlow's model does not contradict error-correction ideas, but its chief goal is somewhat different. The goal of normalizing to contingencies between dimensions, on Barlow's view, is not to reach a "correct" state (of non-correlation between color and form, for example) but to make the organism more sensitive to deviations from the normal sensory contingencies.¹¹

This increased sensitivity is produced in Barlow's (1990; Barlow & Földiák, 1989) model by the automatic decorrelation of sensory dimensions (within a single sense, such as vision or audition) that can be achieved by the modifiable inhibitory connections between them. Barlow (1990) has noted that this is a very different kind of sensitivity gain than that gotten from, say, luminance adaptation. In the case of luminance adaptation, increased sensitivity to luminance differences at any given luminance is obtained by adapting to the prevailing level. In contrast to this sensitivity gain, what the model of modifiable inhibition creates is an orthogonal coding of sensory dimensions that

increases the information capacity of the system relative to the prevailing correlations in the sensory environment.

The mechanisms proposed by Barlow accomplish error correction or recalibration in a very general sense. These can be thought of as *contextual* or *contingent calibration* to emphasize the adaptability of the perceptual system to the contextual influences on perceptual processing. It is reasonable to conceive of contingent adaptation as a kind of learning about interactions between specific environmental attributes (perceptual context) and perceptual processing. Such a sensitivity implies that a sensory system may become differentially attuned to regularly co-occurring sets of circumstances or situations, as in Barlow's formulation. For example, because the prevailing color (or some other property) of various environments may differ from one to another (e.g., outdoors vs. indoors), it might be possible for the visual system's spatial mechanisms to align themselves to the distinct perceptual expectancies of these environments.

Indeed there are anecdotal reports of related phenomena: Sensations of moving backward may be experienced by a frequent bicyclist when pedaling a static exercise machine, or one may feel a subjective reduction in velocity when walking up an escalator that is broken. These experiences are quite suggestive of a contextual calibration of (probably kinesthetic) motion perception. The present experiments are also consistent with (but not determinate of) such an interpretation: The perception of texture density is made contingent on the presence, in another part of the visual field, of particular colors, on the basis of prior experience.

Global Versus Local Adaptation and the Information Processing Approach

Although Barlow's model is limited to local effects, not to long-range interactions, I have argued that the present findings are consistent with local interactions between form and color following on the lateral spreading of color information in the retina (Pöppel, 1986). A strong motivation for this argument is the large body of empirical evidence and theoretical structure that implicate local rather than global accounts of contingent adaptation (but cf. Siegel et al., 1992, 1994; Allan & Siegel, 1993, for an alternative viewpoint). It remains possible that the effects observed here derive from global processes at a later stage of perception than McCollough effects, or, conversely, that they are produced primarily at the texture boundaries where color and form are both present within moderately sized receptive fields. The latter explanation could be tested by a further examination of the spatial characteristics of interaction.

Although I have spoken of an "associative" model of contingent aftereffects, it should be clear that the associations I refer to are quite explicit kinds of computationally efficacious connections between channels of information. Bedford (1995) has suggested that there are no cognitive models of perceptual learning prior to her object-constancy theory. However, analyses of perceptual adaptation are

often stated in information processing terms (see, e.g., Andrews, 1964; Dodwell & Humphrey, 1990). In general, although the units of (conscious) perceptual experience may be objects and events, the units of perceptual processing are not, and this may help to explain why few recent theorists have been tempted to resort to an object-level explanation of contingent aftereffects. This does not make their theories less "cognitive" in any valuable sense. At present it would seem that models such as Barlow's (1990), which make explicit assertions regarding the gain in information processing capacity and efficiency while providing explicit computational models, are not solely physiological nor are they devoid of principled implications for an information processing theory of perception and perceptual learning.

The information processing framework that informs the reasoning in this article is in the tradition of Marr (1982), who emphasized the need for explanation at both functional (computational) and representational levels as well as at the level of implementation. The overarching goal of the visual system (and the perceptual systems generally) is to accurately and efficiently represent or signal the current state of the environment vis à vis the observer. One result of visual processing is normally to give us the sense that we have direct perception of the world. Aftereffects, which indicate that this subjective sense of direct perception may be a kind of cognitive illusion, may also turn out to be a demonstration of processes that, in general, support our direct access to behaviorally relevant information by making no-longer-informative (normal) correlations more or less invisible. The particular model advocated in this paper is one in which the units of interest are simple visual features or dimensions coded locally. It is retinotopically local correlations between these units of information that are stipulated to be compensated for by a model involving quite simple neural assumptions.

Despite the retinotopically local nature of the proposed site of adaptation, the distortions of density evidenced in the current results are produced by information presented in a surrounding context. Although they may be mediated by local interactions, the resulting effect has the appearance of a global effect because information from different portions of the visual field interacts. As an extension of local interactions, the present results suggest that perceptual adaptation of texture perception can be made responsive to somewhat global environmental contingencies such as the prevailing color of light on the retina.

Future Research

Most of my discussion has presumed that the present effect is similar in nature to other visual contingent aftereffects, but further research could help test this conjecture. For example, most contingent aftereffects involving color do not transfer interocularly (Coltheart, 1973), and this could be tested directly in the present effect as well. The density aftereffect itself shows varying degrees of interocular transfer, depending on the concurrent stimulation

to the nonadapted eye during adaptation (Durgin, 1992). Because achromatic balanced dots do not differ from a gray screen at low spatial frequencies, it is possible to observe, dichoptically, a balanced-dot texture in one eye and a matching gray screen in the other without experiencing any binocular rivalry (see also Lehmkuhle & Fox, 1976). Under such conditions the density adaptation in one eye transfers completely to the other. If the unadapted eye is patched during adaptation, however, transfer is typically weaker or sometimes nonexistent (Durgin, 1992). Because color-contingent effects tend to be monocular,¹² it is probable that interocular transfer of the frame-contingent effect would be slight or nonexistent, though the specific conditions of adaptation and testing might be of some importance.

Although longevity is not limited to contingent aftereffects (long-term effects can also be established in simple dimensions, such as orientation, Wolfe & O'Connell, 1986), persistence is a characteristic of most contingent aftereffects involving color. For example, the time course of recovery from color-contingent motion aftereffects is longer than that from achromatic motion aftereffects (Favreau, 1976, 1981). Favreau has shown that for stimuli that specify motion by brightness as well as color, but not for isoluminant motion stimuli, color-contingent motion aftereffects are stronger after a short delay. Favreau has suggested that this results from the interference of motion adaptation in fast-recovering achromatic motion channels with that in slow-recovering chromatic channels. Because the present effect was demonstrated with transient adaptation and test stimuli, it might behave similarly to color-contingent motion aftereffects. However, in Experiment 1 of this paper (but not Experiment 2), evidence was shown of a reduction in aftereffect strength during the few minutes of the test procedure. Of course, this decline may have been accelerated by the testing procedure itself, and further investigations of the time course of the present effect would be useful.

It would also be worthwhile to investigate the relationship between the modified texture perception demonstrated here and the long-term visual learning observed by Karni and Sagi (1991, 1993). According to the arguments presented above, both kinds of learning can be construed as modification of texture representation with a beneficial effect on texture coding efficiency. It is possible that the similarity between the effects may be investigated further to elucidate specific coding processes involved in the visual analysis of texture information.

Summary

Like color and motion aftereffects, aftereffects of spatial pattern can be made contingent on information in a surround. Specifically, the perceived density of visual texture can be made contingent on color information presented in a separate location in the visual field. The strength of this contingent aftereffect appears to depend on the quantity of color information presented. I have suggested that

this effect may be related to other aftereffects of spatial vision that have been made contingent on color. I have also argued that the effect may depend on the retinal spreading of color information and conjectured that this effect can be interpreted in terms of a local, inhibitory, associative theory of contingent adaptation, such as Barlow's (1990). Contingent modifications of texture perception may reflect visual tuning or calibration in the visual processing of texture.

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NOTES

1. It is, of course, possible that the "spread" color information will interact nonlinearly with the color-specific texture registration mechanisms, producing a color bias in their activation.

2. Durgin and Proffitt (in press) have suggested that contrast-edge-polarity contingent color adaptation may be closely related to the elimination of color fringes due to chromatic aberration (from prism glasses, for example; see Held, 1980) that may have inspired the McCollough effect.

3. The blue was made light so as to better match the brightness of the yellow.

4. Such textures appear quite dense but clearly have a figure (the dots) and ground (the black background) in a way that a 50% filled random pattern does not.

5. The number of dots in the test textures was always less than the dense-adapting textures so that the presentation of test textures would produce less (unbiased) interfering adaptation, which might cancel or conceal the contingent aftereffect being measured.

6. I have also performed analyses of the untransformed PSE scores in all the experiments reported here. In every instance the same statistical conclusions are supported.

7. Compared to a mean aftereffect size of 0.045, with a standard deviation of 0.095 for the other 21 subjects. This subject's aftereffect score was 0.65. Including this subject's data in calculation of mean and standard deviation, it is 3.64 standard deviations above the mean.

8. Compared to a mean aftereffect size of 0.063, with a standard deviation of 0.083, for the other 11 subjects, this subject's aftereffect score was -0.41 . Including this subject's data in calculation of mean and standard deviation, it is 2.75 standard deviations below the mean.

9. The border contains 7.3 times the number of pixels as the central stripe. In terms of visual angle, the ratio of areas is approximately 7 (due to the increased viewing distance to the outer portions of the display).

10. This statement is based on unpublished results from studies done in collaboration with D. Proffitt. We adapted observers to fairly sparse texture fields and found a very slight decrease in perceived density in the sparse-adapted regions, rather than an increase.

11. Barlow (1990) used an example of normal correlations between motion parallax and binocular stereopsis to show how our perceptions seem to normalize to correlations: Head movement while viewing a stereogram (i.e., a pair of static 2D images viewed dichoptically to produce a 3D image) produces a powerful *sensation* of concomitant object rotation, in compensation for the *absence* of normal motion parallax.

12. Traditionally, color effects are presumed to be monocular because of underlying neurophysiology (Coltheart, 1973). Different color-specific calibrations might indeed be appropriate (especially locally on the retina) for the different eyes.

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