At mesopic mean luminances, a fixed luminance contrast produces less brightness contrast than it does at photopic luminances. This suggests that lightnesses of surfaces might also be altered at low luminances. I measured lightness, brightness, and brightness contrast in CRT simulations of achromatic paper patchworks. The illuminance of the standard pattern was fixed, producing 0.12, 1.2, or 12 cd/m^2. The illuminance on the test pattern was varied in a lightness constancy paradigm. Constant brightness contrast required more luminance contrast at lower mean luminances. Failures of lightness constancy occurred at the lowest mean luminances, but they were minor in comparison with the loss of brightness contrast in the same pattern. These results have implications for imaging applications. Often, image content falls in both the photopic and the mesopic ranges. Our results indicate that brightness contrast may decrease substantially in low-luminance regions without large changes of surface lightness.

The experiments described below are part of a series designed to reveal limitations that early visual processes place on perception of surface colors. In their 1984 review of psychophysical and neurophysiological studies of adaptation, Shapley and Enroth-Cugell argued that retinal adaptation serves the crucial function of approximately encoding local illuminance contrast in the retinal image. Prior work has shown that the approximation is good under some viewing conditions but far from ideal under others. In particular, at low mean luminances, a fixed luminance contrast produces less brightness contrast than it does at higher mean luminances (Whittle, in press; Whittle & Challands, 1969).

According to several theories, lightnesses and lightnesses in complicated images are derived from signals specifying the luminance contrasts of edges (Arend & Goldstein, 1987a; Blake, 1985; Horn, 1974; Land & McCann, 1971). If so, Whittle and Challands's (1969) data indicate that lightnesses of surfaces might also vary substantially as a function of mean luminance.

Some preliminary evidence on this point has emerged in recent experiments with complex luminance arrays (Arend & Spehar, 1993a, 1993b). We measured brightness, lightness, and local brightness contrasts over a 19:1 range of mean luminances. We used Mondrian patterns (Figure 1 of Arend & Spehar, 1993a), which we consider to be a useful compromise between natural images, which are usually too complicated to analyze and control, and traditional disk/annulus patterns, which provide too little information to support surface color perception. To simplify the analysis of local brightness contrasts, we placed the square test patch in the center of a larger square patch so that it was completely surrounded by a single luminance, and both were centered in a larger Mondrian of 27 rectangular patches. A standard patch was surrounded by a spatially identical pattern. The surround fields of the standard and test patches had different simulated reflectances. Under these conditions, the observers could make three distinct kinds of matches between the test and standard patches, brightness, lightness, and brightness contrast.

At this point, it is necessary to define brightness, lightness, and local brightness contrast. For the first two, standard definitions are available, but for our purposes, we can use definitions of them that are agreed upon by the Trieste Group. They are similar to the CIE and OSA definitions, but slightly clarified and simplified. Lightness is thus defined as apparent reflectance; brightness is defined as apparent luminance, the apparent amount of light coming from a visual direction.

There is no similarly accepted definition of local brightness contrast. In the case of interest here—brightness contrast at a sharp edge between two uniform regions—a very simple definition is sufficient. Local brightness contrast is the local brightness difference between a target and its immediate background. We used sharp-edged patches, both to enable this simple definition of brightness contrast and to allow relatively straightforward comparisons with previous research, but it should be noted that other kinds of spatial luminance gradients also occur frequently in natural scenes. Luminance gradients range from sharp to very gradual, and patches of relatively uniform luminance are seldom surrounded by a single uniform luminance. Some possible approaches to such stimuli are discussed in the Results section.

We chose to simulate illumination changes across a single scene rather than changes over time of the general il-

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lumination level, because the former present much greater challenges to the visual system's lightness constancy mechanisms than do the temporal changes. The arguments are too lengthy for detailed discussion here. A thorough discussion is presented elsewhere (Arend, in press).

Briefly, it can be stated that when observers look at a scene with shadowed and shaded regions, they move their eyes rapidly from region to region, in a pattern that is controlled in part by their immediate tasks. Both patterns of reflectances and shading patterns carry information about the spatial layout of the environment and are represented in consciousness. Perceptual mechanisms must cope with spatially varying light levels at high speed. Spatial luminance gradients must be vector analyzed into reflectance and illumination components so that both can be perceptually represented. Temporal illumination changes over the entire scene are less interesting as information for behavioral choices. They can be dealt with by relatively simple strategies that change the global sensitivity of the visual system.

In the earlier experiment (Arend & Spehar, 1993a), we found that lightnesses were illumination invariant and closely approximated reflectance matches. Equating the local luminance ratios produced equal local brightness contrasts at the higher illumination levels, but higher luminance ratios were required at low mean luminances.

In this extension, we measured lightnesses, brightnesses, brightness contrasts, and contrast thresholds of stimuli ranging from photopic mean luminances down to mesopic luminances. Luminance-contrast efficiency declined as mean luminance was decreased; that is, a fixed luminance contrast produced less brightness contrast. However, this did not interfere with lightness constancy. Lightnesses were nearly invariant over the full range of illuminations. Brightness-contrast matches departed from Weber's law at roughly the same background luminances as did contrast thresholds measured under the same conditions.

**METHOD**

We measured lightnesses, brightnesses, brightness contrasts, and contrast thresholds in CRT simulations of achromatic paper patchworks. The illumination on the test pattern was varied from trial to trial in a lightness constancy paradigm.

**Stimuli**

The stimuli were simulations of uniformly illuminated matte papers lying in a common depth plane. For brevity, we will hereafter drop the simulation terminology and refer to the stimuli and their simulated properties as though they were actual papers. Discussions of the relationship between real illuminated scenes and CRT simulations of those scenes can be found in Hochberg (1986), Arend and Spehar (1993a) and Arend (in press).

The stimulus patterns were those of the unequal-surround-reflectances condition of Arend and Spehar (1993a) (Figure 1). Two 1°-square patches were presented 7.5° apart (center to center). Each patch was surrounded by a gray, square surround whose inner border coincided with the edge of the patch and whose outer border subtended 3°. These uniform annuli were each surrounded by a patchwork of small rectangles (a Mondrian), arranged in the shape of a square surround with a 3°-square inner border and 5°-square outer border. The two patchwork arrays had identical spatial arrangements of 27 irregular rectilinear patches, with reflectances ranging from 0.03 to 0.95 (1.50 log units).

There were two reflectance conditions with different combinations of patch-and-surround reflectances. These particular reflectance combinations were chosen to give large separations of theoretical predictions for the three matching tasks (described below).

The subject adjusted the simulated reflectance of the test patch. The reflectances of all patches but the test patch and the illuminance of the left pattern (standard array) were fixed within each session. In the increment condition (Arend & Spehar, 1993a, Figure 1a), the standard patch and surround were light grays (R = 0.60; Munsell value V = 8.2/ and R = 0.40; V = 7.0/), respectively. The test surround was a dark gray (R = 0.10; V = 3.8/). In the decrement condition (Arend & Spehar, 1993a, Figure 1b), the standard patch and surround were dark grays (R = 0.14; V = 4.4/ and R = 0.21; V = 5.3/), respectively. The test surround was white (R = 0.81; V = 9.2/). In the standard array, the ratio of patch reflectance/surround reflectance in the increment condition was the inverse of that in the decrement condition.

The mean luminance of the display was controlled by a combination of two factors. Neutral density filters were placed in front of both eyes to reduce the luminances in both the test and the standard arrays by the same factor. In separate sessions, filters reduced the luminances by 1.0 and 2.0 log units below those of Arend and Spehar (1993a). The standard array had mean luminances of 12.3 cd/m² in the Arend and Spehar experiment (no filter), and 1.23 and 0.123 cd/m² in the new conditions, produced by neutral densities of 1.0 and 2.0, respectively. The second luminance factor was the simulated illuminance on the test array. Within each of the three filter conditions, the illuminance of the right pattern (test array) changed from trial to trial, in randomized blocks of five values, spanning a range of 1.28 log units in equal logarithmic steps.

We chose to reduce the luminances of both arrays in order to allow free binocular viewing that would approximate natural vision at low luminances. The subjects were asked to spend about the same amount of time in looking at the test and at standard patterns and to alternate their gaze between the patterns, shifting approximately once every 2 sec. This regimen was an attempt to simulate a comparison of two regions in natural vision. In pilot work, we found that illumination differences greater than 1.28 log units between the two arrays prevented the observer from alternating fixation between the two arrays. With larger differences, the low brightness contrast of the test array and the rapid adaptive changes produced an irresistible desire to remain fixated on the test array until its brightness contrast was greater. Shorter glances did not allow confident assessment of the perceptual property in question. Longer fixations produced noticeable temporal changes of brightness and brightness contrast.

Current opinion regarding achromatic adaptation appears to be that mechanisms with very short time constants (on the order of tens of milliseconds) coexist with much slower mechanisms (see Hayhoe & Wenderoth, 1991, for a recent review). It is clear that some adaptation processes will have run their course by the end of the 2-sec fixations, whereas others will have just begun. The very small variability of the data reported below, reasonable agreement with data from other paradigms, and the absence of salient changes of appearance during the fixations suggest that the mechanisms produced adaptation adequately stable for our purposes. For further discussion of eye movements and adaptation, see Judd (1940) and Arend and Spehar (1993a).

The luminance, L(p), of any particular patch, p, is given (in cd/m²) by

$$L(p) = 47.0 \times F \times \frac{E_{\text{test}}}{E_{\text{std}}} \times R(p),$$

where F is the filter factor (1.0, 0.1, or 0.01), E_{\text{test}}/E_{\text{std}} is the ratio...
of the illuminance on the test pattern (including \( p \)), and \( R(p) \) is the reflectance of \( p \). The patterns appeared on a 14.2°-square dark surround (0.014 cd/m² in the 0.0 filter condition, 0.006 of the luminance of the darkest patch of the standard Mondrian) in an otherwise completely darkened room.

**Equipment**

The gray patterns were presented on a carefully calibrated Tektronix 6905SR high-resolution color monitor under the control of an Adage 3000 image processor and a VAX-11/750 minicomputer. Details of the apparatus and calibrations can be found in previous papers (Arend & Reeves, 1986; Arend & Spehar, 1993a).

The gray-scale patterns had the same chromaticity (6500 K) over the required luminance range and varied only in luminance, as programmed. Chromaticity and luminance were adequately uniform over the effective viewing area, and the display was stable within and between sessions. The functions relating digital data to luminance in the red, green, and blue channels of the image processor/display system were measured. A linear relationship was obtained in each color channel through 10-bit look-up tables derived from the direct luminance measurements. To evaluate the resulting luminance curve, output luminances were directly measured. The curve was linear and accurate to very low luminances in all three guns.

The subjects controlled the luminance of the test patch by moving a hand-held cursor horizontally over a high-resolution graphics tablet. Between trials, the computer randomly offset the relationship between hand position and luminance within a range of ±10% to prevent position cues from influencing the matches. The spatial resolution of the tablet exceeded the 10-bit resolution of the image processor’s D/A converters.

**Procedure**

Subjects initially adapted for 3 min to a 14.2° × 14.2° visual angle, 6500 K, uniform white field of the mean luminance of the standard array of the session. They then viewed the two continuously presented displays and matched the test patch in the right display with the corresponding standard patch in the left display, using the tablet to vary the test patch luminance. The match was made to satisfy one of the three task criteria, described below.

Five adjustments at each of the five illuminances, for one of the three tasks in both the increment and the decrement conditions, constituted an experimental session, requiring approximately 20 min. No more than two sessions per day per subject were run, separated by at least 15 min of rest time.

**Tasks**

There were four tasks (brightness, lightness, brightness contrast, contrast threshold) in each of the experimental and control conditions.

In the lightness-matching condition, the observers were instructed to make the test patch "look as if it were cut from the same piece of paper" as was the corresponding patch in the standard. It was pointed out that the outer, Mondrian, surround spanned a range of grays from black to white.

In the brightness-matching condition, the observers were instructed to make the test patch "have the same brightness as the corresponding patch in the standard, disregarding, as much as possible, other areas of the display. That is, make the amount of light coming from the test patch look the same as that from the standard."

In the brightness-contrast task, the observers were instructed to "make the brightness difference between the test patch and surround the same as that between the standard patch and surround."

In the contrast-threshold task, the observers were instructed to adjust the test patch to be just detectably brighter (increment condition) or darker (decrement condition) than the inner surround.

**Subjects**

Two of the observers from the prior experiment (Arend & Spehar, 1993a) participated, the author and a paid observer (D.A.). D.A. was experienced in lightness and brightness matching, but naïve with respect to the purpose of the experiment.

**RESULTS**

For reference, Figure 1 shows the data of 1 subject for all three tasks at the highest mean luminances. The horizontal axis shows the log of the ratio of illuminance on the test array to that on the standard array. The test illuminance equals the standard at 0.0 and declines to the left. The subject adjusted the luminance of the test patch to match it with the standard patch, but it is convenient for theoretical reasons to plot the data as though the subject were adjusting the reflectance of the test patch. The subjects’ mean log reflectance settings (mean log lu-
minance — log illuminance) are plotted as ordinates. For comparison, the Munsell values corresponding to the log reflectances of the left vertical axis are indicated on the right vertical axis.\(^3\) The circles in each panel are the means for the lightness task. The top horizontal solid line in the increment condition (top panel) and the bottom horizontal solid line in the decrement condition (bottom panel) are the theoretical perfect lightness-constancy lines, reflectance matches. For the increments, the data lie approximately on the theoretical line. For the decrements, they lie approximately 0.2 log units above the line. In both cases, the data lie along a nearly horizontal line, indicating that the data are approximately illumination invariant. The squares show the brightness matches. The solid line with slope \(-1\) is the locus of reflectances that would produce a photometric match of the test and standard patches. For both increments and decrements, the slopes of the brightness curves deviate from \(-1\) toward that of the reflectance-match line. As in previous experiments (Arend & Goldstein, 1987b, 1990), the slope is closer to \(-1\) for increments. The brightness-contrast matches are shown by the triangles. The lower horizontal solid line in the increment condition (top panel) and the upper horizontal solid line in the decrement condition (bottom panel) show the log reflectance of the test patch for which the ratio of patch luminance to surround luminance in the test array is equal to that in the standard. At the highest illuminances, the brightness-contrast data fall approximately on the equal-ratio line, but for increments, the luminance ratio required to maintain constant brightness contrast declined monotonically as the test illuminance declined. At these mean luminances, the decline was small but repeatable, and it occurred for all 3 subjects.

Now consider just the brightness-contrast data at all three mean luminance levels (Figure 2). The luminance contrasts required to maintain constant brightness contrast were substantially greater at the lower luminances, especially in the increment condition. The filters reduced the mean luminance of the standard array and the range of illuminances on the test array proportionally. Therefore, the brightness contrast of the standard array was expected to decline at the higher filter densities, and this was subjectively observed. Nevertheless, the rate at which the luminance contrast of the test patch/surround needed to be increased to maintain constant brightness contrast was greater at the lower mean luminances (steeper negative slope). The effect was much stronger for increments than for decrements. There are two likely contributors to the smaller effect for decrements. First, at all illumination levels, the luminance of the surround was higher for decrements than for the corresponding increments, because of the higher reflectance of the surround. Second, decrements follow the Weber relation to lower luminances than increments do (Whittle, in press; Whittle & Challands, 1969).

The slopes can be understood by replotting the data in coordinates analogous to Whittle and Challands's (1969) (Figure 3). The lowest, overlapping data sets are contrast thresholds. The change of coordinates has the effect of rotating the theoretical curves and data of Figure 2 counterclockwise by 45°. Equal luminance ratios thus lie on a line of unit slope. The data lie on three different constant brightness-contrast curves, owing to the lower brightness contrasts of the standards at the reduced mean illuminances. The 1.23-cd/m² standard is only slightly reduced in brightness contrast, but the 0.123-cd/m² curve is substantially lowered. The solid curves are Stiles's template, translated by eye to fit the four data sets. The luminance range within each condition is too small to draw strong conclusions from the required translations of the template, but it appears that the suprathreshold curves are shifted to the left of what one might expect from Whittle and Challands's data, especially for the decrements. As in our suprathreshold curves, they found that the template shifted upward and to the right with increasing brightness contrast of the standard, but in their
Figure 3. Brightness-contrast matches plotted in coordinates analogous to Whittle and Challands's (1969). Overlapping lower curves: increment thresholds. Solid lines: Stiles's template, shifted by eye. Open squares: 12.3 cd/m² mean luminance. Dotted squares: 1.23 cd/m² mean luminance. Filled squares: 0.123 cd/m² mean luminance. (a) Observer L.A. (b) Observer D.A.

Data, the contrast thresholds lay at the bottom end of the series, down and to the left of all of the suprathreshold curves.

If the required patch luminance were to decrease in proportion to decreasing surround luminance, the data would have unit slope. Instead, as in Whittle and Challands's (1969) experiment, the required patch luminance declined ever more slowly as the mean luminance fell—that is, luminance-contrast efficiency declined.

On the other hand, changes in the mean luminance of the test pattern had little effect on the apparent reflectance (lightness) of the surface (Figure 4). For increments (upper three curves), there were no differences of lightness corresponding to the large changes of brightness contrast at the same mean luminances. Lightness constancy was nearly perfect. For decrements (lower three curves), the three curves diverged slightly, but only at the lowest mean luminance.

For decrements, there was a small (<0.2 log units) constant departure from lightness constancy. This is probably attributable to local simultaneous contrast due to the difference between the reflectances of the test and standard surrounds. Since the error was independent of illumination, lightness was illumination invariant. No corresponding error occurred for increments. A systematic study of this effect of background reflectance has been completed and is being published elsewhere.

The lightness matches are replotted in Figure 5 for comparison with Figure 3. As in Figure 4, the solid line is the equal-reflectance theoretical line (perfect lightness constancy). The increment data have unit slope at mean luminances well below the bottom of the Weber's law region for contrast thresholds.

Brightness matching (Figure 6) showed less consistency between subjects than did the other two tasks. The 0.123-cd/m² curve was consistently below the other two for
Figure 4. Mean log reflectance data from lightness condition. Top three curves: increments. Bottom three curves: decrements. Solid lines: equal reflectances (perfect lightness constancy). Open squares: 12.3 cd/m² mean luminance. Dotted squares: 1.23 cd/m² mean luminance. Filled squares: 0.123 cd/m² mean luminance. Error bars are ±1 SE (n = 5). If no bar is visible, ±1 SE is smaller than the plot symbol. (a) Observer L.A. (b) Observer D.A.

Subject D.A., but there were no consistent differences in L.A.’s data. As in our previous experiments (Arend & Goldstein, 1987b, 1990), the brightness curves for decrements were all farther from luminance matches than were the brightness curves for increments.

Comparison across mean luminance conditions is more difficult for the brightness matches than for lightness and brightness contrast, because of the lack of a common reference. We can, however, safely conclude that the brightness of the test patch varied substantially as a function of illumination over the entire range of illuminances.

DISCUSSION

These results have implications for a wide variety of imaging applications. Luminances in pictures frequently range downward from about 100 cd/m², the maximum luminance of common television sets, CRT monitors, and photographs under room lights. Often some scene content will fall in the photopic range and some in the mesopic range. Our results indicate that brightness contrast should decrease in low-luminance regions without producing correspondingly important changes of surface lightness.

The first part of this conclusion, the loss of brightness contrast, is no surprise to the applied color community. Hunt (1952, 1987), Evans (1974), and others have documented the decrease of color and brightness contrast at low luminances. It is worth noting, however, that the experiments and discussions have been cast in terms of absolute saturation and brightness rather than apparent contrast, which is a measure of saturation and brightness relative to other colors in the region. The distinction might be made clearer by a hypothetical example. Let us suppose that the mean luminance of a shadowed portion of a scene is such that the apparent color difference between the red surface of an apple and the green surface of a leaf is only half that in a highlighted region of the scene. This loss of chromatic contrast might result in desaturated hues symmetrically arranged about achromatic, but it might

Figure 5. Lightness matches plotted in coordinates analogous to Whittle and Challands’s (1969). Top panel: increments. Bottom panel: decrements. Solid lines: theoretical lines, explained in text. Open squares: 12.3 cd/m² mean luminance. Dotted squares: 1.23 cd/m² mean luminance. Filled squares: 0.123 cd/m² mean luminance. (a) Observer L.A. (b) Observer D.A.
A black suit and white shirt may look black and white even when the luminance contrast is drastically reduced by the veiling luminance of a reflection in the store window. Gilchrist and Jacobsen (1983) studied veiling reflections experimentally and found that they interfered little with lightness constancy.

I have sketched the outlines of the type of model (Arend, 1991, in press) that seems to be required to account for human competence at perceiving the properties of surfaces under those and other challenging viewing conditions. The model borrows heavily from computer vision models originally proposed by Barrow and Tenenbaum (1978) and Marr (1978). In my model, adaptation and other early visual processes contribute to surface perception only by providing a visual signal that represents illumination contrast in the retinal image more accurately than would be possible in their absence (no small contribution). They do not directly provide an array of values that locally specify the properties of surfaces in the scene. Perceptual assertions about surface properties are made at a subsequent stage in which the visual system uses the current image information and a wide variety of constraining assumptions to cooperatively compute a best guess about all the physical optical conditions that interact to produce the retinal signals. For example, the automatic computation that lets me perceive the same colors of birch bark and leaf in sunlight and fog also tells me about the fog. The color constancy is not achieved by making the fog invisible in the way that a brightness-contrast-enhancing image-processing algorithm would, but by accurately representing all the relevant optical variables. Adding Mondrian fields is not the only way to cause luminance changes to be confidently perceived to be illumination changes. Any complicated spatial pattern of luminances that covary in the manner that would be produced by illumination differences will be perceived as such.

Since we apparently automatically compute the effects of fog and veiling luminances to at least a first approximation, it seems possible that we can also automatically include in our perceptual computations the more frequently encountered effects that low mean luminances have on our early adaptation mechanisms.

REFERENCES


Figure 6. Mean log reflectance data for brightness conditions. Top three curves: increments. Bottom three curves: decrements. Solid lines: equal luminances. Open squares: 12.3 cd/m² mean luminance. Dotted squares: 1.23 cd/m² mean luminance. Filled squares: 0.123 cd/m² mean luminance. Error bars are ± 1 SE (n = 5). If no bar is visible, ± 1 SE is smaller than the plot symbol. (a) Observer L.A. (b) Observer D.A.


NOTES


2. Both observers participated in the prior experiment (Arend & Spehar, 1993a, 1993b) and were familiar with the tasks. Nevertheless, to remind the observers of the criteria, the written instructions were read before the initial session of each condition and approximately every 3rd day thereafter.

3. Since the viewing conditions here are different from those used to develop the Munsell value scale, the numbers should not be considered as anything more than a first approximation to expressing the appearance of the patches. They are, however, the Munsell papers one would need to use if one were constructing the stimulus from real papers and lamps.

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