Color appearance depends on the variance of surround colors

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Background: The perceived color at each point in a visual scene depends on the relationship between light signals from that point, and light signals from surrounding areas of the scene. In the well known phenomenon of simultaneous color contrast, changing the overall brightness or hue of an object's surround induces a complementary shift in the perceived brightness or hue of the object's color. Color contrast is thought to contribute to color constancy with changes in illumination.

Results: We report a new type of simultaneous color contrast, in which changing only the variance (i.e. contrasts and saturations), but not the mean, of colors in a test spot's surround induces a complementary shift in the perceived contrast and saturation of the test spot's color. Objects appear much more vivid and richly colored against low-contrast, gray surrounds than against high-contrast, multicolored surrounds.

Conclusions: Color appearance depends not just on the mean color of the surround, but also on the distribution of surround colors about the mean. This novel form of simultaneous color contrast is inconsistent with a variety of models of color appearance, including those based on sensitivity regulation at the receptor level, and those in which the effects of complex surrounds on color appearance can be reduced to adaptation to the illuminant or induction from a homogeneous 'equivalent surround'. It tends to normalize the gamut of perceived colors in each visual scene and may also contribute to color constancy under viewing conditions that affect contrast.

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Background

Although we commonly experience colors as local properties of colored objects, color appearance is not determined by the local light signals from each object, but instead depends on relative light signals across the visual scene. How these light signals are integrated to generate perceived colors is an essential problem for understanding color vision. In classical simultaneous color contrast, objects acquire brightnesses and hues complementary to the brightnesses and hues of their surrounds [1–3]. Because the contrasts in scenes remain relatively constant when the illumination changes, color contrast is thought to provide a mechanism for color constancy.

Color contrast has generally been studied using test spots with homogeneous surrounds, whereas color vision under natural conditions commonly involves complex heterogeneous surrounds. The question we address here is whether the problem of color contrast in complex surrounds can be reduced to the relatively well understood problem of color contrast in uniform surrounds. Such a simplification is implied by many popular models of color appearance, such as those based on 'von Kries-type' sensitivity regulation in the photoreceptors [4–6], and those in which heterogeneous surrounds are predicted to have homogeneous 'equivalent surrounds' [7–9]. In general, these approaches predict that color appearance depends on the mean light from surround colors, but not on the distribution of the surround colors about their mean. In the present experiments, we studied the effects on color perception of surrounds that had identical space-averaged means, but different variances.

Results and discussion

We found that color appearance was dramatically affected by the variance of surround colors, even when the space-averaged light from the surround was constant. A calibrated, computer-generated video display was used to create complex multicolored stimuli. This enabled us to easily manipulate the variance while holding the mean approximately constant. Examples of the stimulus patterns we used are reproduced in Figure 1. Six low-contrast rectangles, spanning a compact gamut of grayish colors distributed around 50% gray, were embedded in various surrounds. The surrounds all had the same space-averaged color (50% gray), but differed in their variance, that is, the gamut of colors constituting the surround. When the six rectangles were embedded in a high-contrast mosaic of richly colored squares (Figure 1a), they appeared as six indistinct, washed-out shades of gray. But six physically identical rectangles, when embedded in a uniform, 50% gray background (Figure 1b), appeared much more distinct and colorful, and encompassed an expanded gamut of perceived colors. This was a striking and unexpected effect, and many observers were skeptical that the rectangles could really be physically the same in the two surrounds (see Materials and methods for measurements verifying this critical point). This 'gamut expansion' in low-contrast gray surrounds (or, equivalently, 'gamut compression' in high-contrast colored surrounds) occurred simultaneously in the white, black, red, green, blue and yellow directions. Thus, unlike the classical forms of simultaneous color contrast for brightness and hue, it cannot be explained as simply an adaptive translation of the 'white point', but corresponds instead to an expansion of colors in all directions about the neutral point.

In quantitative experiments, subjects alternately viewed the reference display, comprising six fixed rectangles embedded in a uniform 50% gray surround, as shown in Figure 1b, and an experimental display, with six corresponding test rectangles embedded in one of the colored surrounds, such as that in Figure 1a. Subjects adjusted the colors of each of the six test rectangles in the colored surround to achieve the best possible perceptual match with its corresponding reference rectangle in the gray surround. Note that a matching procedure was essential for measuring these gamut expansion effects; the cancellation method only measures translations of the neutral point, but would not capture the present phenomenon of changes in the gain for color variance about that neutral point [10].

The color of each rectangle was a binary mixture of the 50% gray, and one of the six endpoint colors (white, black and four saturated hues), determined by the gamut available on our monitor. We use the measure 'richness' to quantify the proportion of endpoint color in each mixture, with 50% gray representing zero richness, and maximal white, black and saturated colors representing unity richness. Richness may be considered the antonym of 'grayness', and is roughly a generalization of the term saturation, which measures only the chromatic variance from the achromatic axis, that encompasses both chromatic and achromatic variance from the origin at 50% gray. All the reference rectangles were presented at 12% richness. Our data for the matches are expressed in 'relative richness', which is the ratio of the subject's experimental richness settings for the test rectangles to the 12% richness of the reference rectangles. (Note that the dependence of richness on the available display gamut is eliminated by taking these ratios for relative richness.)

In the first experiment, 12 naive subjects viewed the six reference rectangles in the uniform 50% gray surround, and adjusted the richnesses of six corresponding test rectangles in either an identical 50% gray surround or in a colorful mosaic surround, such as that in Figure 1a. In the control, symmetric matching condition, the subjects' matches of rectangles between two identical 50% gray surrounds were almost veridical, as shown by relative richness settings near unity for all six colors in Figure 2 (gray surround). In the asymmetric matches, shown in Figure 2 (colored surround), the six rectangles in the high-contrast colored surrounds required relative richnesses of about three to four in order to match the rectangles in the uniform 50% gray surround. This demonstrates

Figure 1

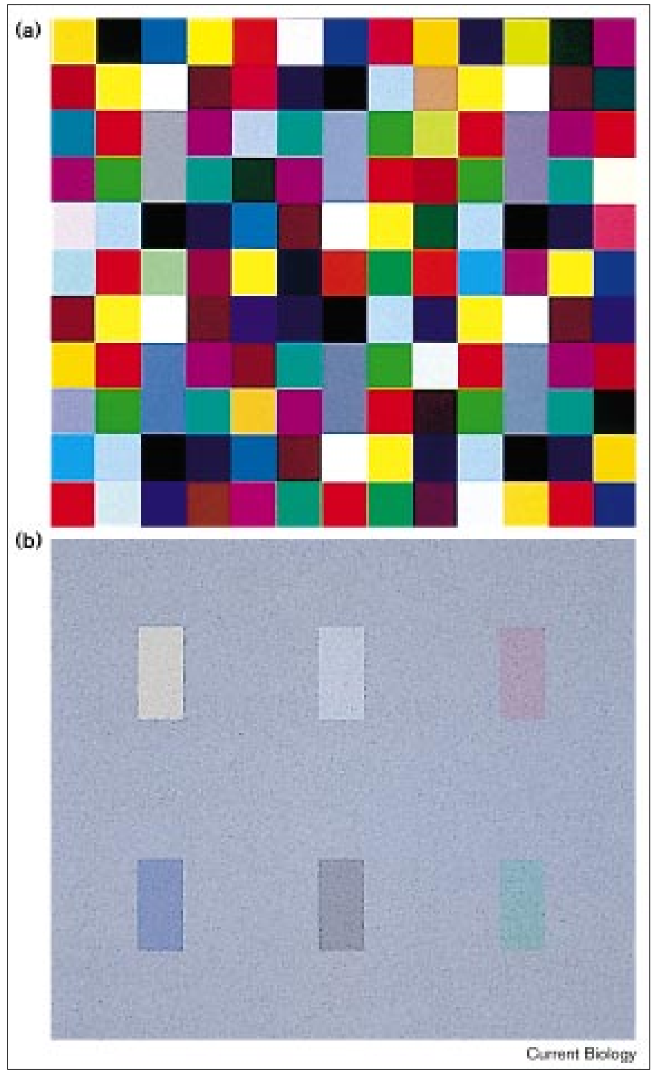
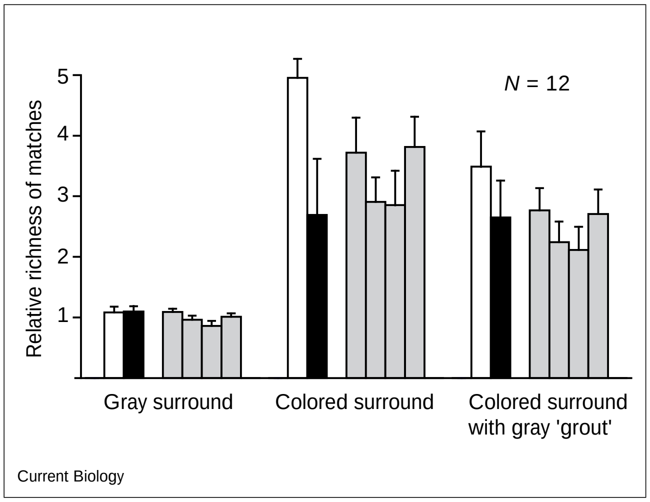


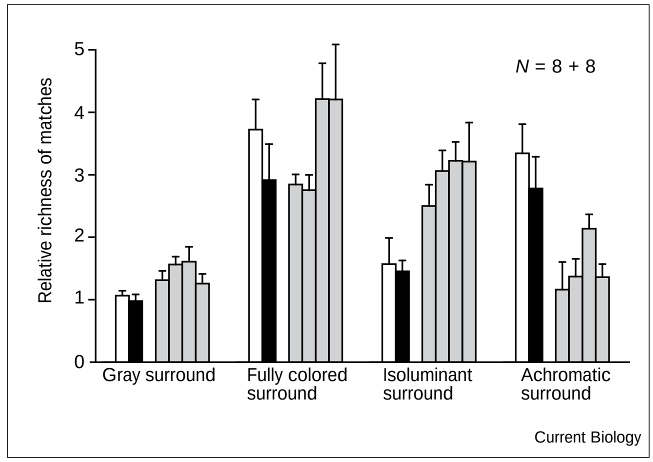
Illustration of stimuli. Two surrounds, with the identical space-averaged luminance and chromaticity, but different variances around that average, produce very different effects on the perceived colors of six embedded test rectangles. The six rectangles were predominantly gray tinged with yellow, white, red, green, black and blue (clockwise from upper left rectangle). **(a)** In a high-contrast richly colored surround, the six rectangles all appeared grayish and were difficult to discriminate from each other. **(b)** In the uniform gray surround, the six rectangles, which were each physically identical to the corresponding six rectangles in (a), appeared to be much more richly colored. Note that the precise stimuli displayed on the calibrated monitor in our studies can only be approximated by this photographic illustration.

Figure 2



Gamut compression in colored surrounds. Six reference rectangles were all presented at 12% richness in uniform 50% gray surrounds. Subjects adjusted the richnesses of six corresponding rectangles in either an identical 50% gray surround, a fully colored surround with high-contrast edges between squares and rectangles, or a fully colored surround with thin 50% gray 'grout' separating all the squares and rectangles from each other. A veridical match to the reference rectangles, in which subjects set test rectangles also at 12% richness, corresponds to a relative richness of 1. The heights of the bars indicate the relative richnesses set for the rectangles in each type of surround in order to match the corresponding reference rectangles in the uniform gray surround. Note that relative richnesses > 1 correspond to gamut compression by the corresponding colored surround, as more color was necessary to achieve a match. Any overall biases in the brightness or chromaticity induced by the surrounds were removed by subtracting the settings for matches to 50% gray rectangles in a control condition. Each bar represents the mean results from 12 subjects for one of the six rectangle colors: the white and black bars represent matches to the achromatic, white and black rectangles and the gray bars represent matches to the red, green, yellow and blue rectangles. Error bars indicate s.e.m.

Figure 3

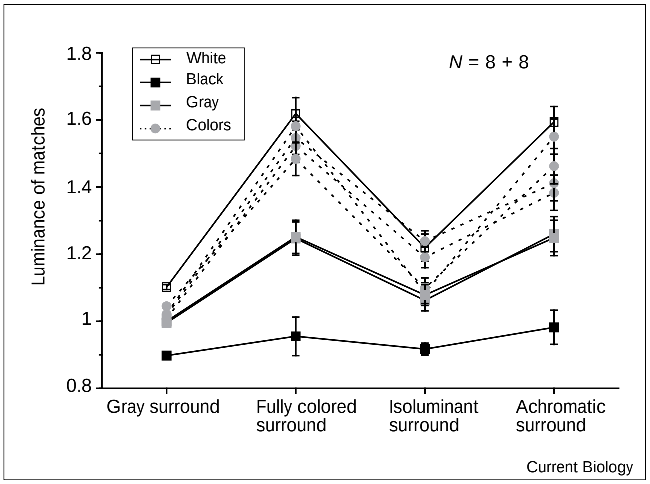


Double dissociation of brightness and chromatic effects. In this experiment, 16 subjects were split into two groups. For both groups, three of the six rectangles were achromatic, with endpoint colors of black, white and 50% gray. The other three rectangles were isoluminant with 50% gray, and varied along one of two chromatic axes for each group. Eight of the subjects were presented with purple, gray and green rectangles while the other eight saw cyan, gray and gold rectangles. Subjects simultaneously adjusted both the luminance and the saturation of the chromatic rectangles to achieve best perceptual matches. The relative richnesses represented by the bars are as in the previous figure, and correspond only to the color dimensions along which the reference rectangles varied from 50% gray. Four types of surrounds were used: 50% gray surround and fully colored surround as before, plus achromatic surround with only luminance variance, and isoluminant surround with only chromatic variance. No 'grout' was used.

a strong compression of the gamut of perceived colors in the colored surround relative to the gray surround. In a third condition, thin (8 min of visual arc) lanes of 50% gray 'grout' separated all the squares and rectangles in the colored displays, so that the rectangles had the same immediate local surrounds in both the colored and test displays. As shown in Figure 2 (colored surround with gray grout), this reduced but did not eliminate the gamut compression effect, indicating that the effects of color variance in the surround cannot be entirely local.

The second experiment was designed to independently examine the luminance and chromatic dimensions of this gamut expansion effect. The six reference rectangles were varied from 50% gray along either the achromatic axis (black to white), or an isoluminant chromatic axis (either cyan to gold or purple to green). Four experimental colored surrounds were used: the control, uniform 50% gray surround and three multicolored surrounds. The first of these was fully colored, as in the previous experiment, with both luminance and chromatic variance; the second was achromatic, with only luminance variance; and the third was isoluminant, with chromatic variance but minimal luminance variance. The subjects' task was similar to that in the first experiment, except that they independently adjusted both the luminance and the saturation of the chromatic rectangles to achieve two-dimensional matches. The results for symmetric matches in the 50% gray surround (Figure 3, gray surround), and for asymmetric matches in the fully colored surround (Figure 3, fully colored surround), replicated the results in the first experiment. Again, all six rectangles in the fully colored surround required about three to four times the richness of those in the gray surround. The achromatic surround with luminance variance primarily affected the appearance of achromatic rectangles (Figure 3, achromatic surround), whereas the isoluminant surround with chromatic variance primarily affected the appearance of chromatic rectangles (Figure 3, isoluminant surround). This double dissociation of the luminance and chromatic dimensions of the gamut expansion effect suggests independent gamut normalization in the

Figure 4



Luminance bias in colored surrounds. The mean luminances of the matches from experiment 2 are shown for the seven test colors and four surround types. All 16 subjects made matches to the black and the white reference rectangles, shown by the black and the white squares connected by solid lines. The black and the white reference rectangles had 12% lower or higher luminance, respectively, than the 50% gray. All remaining reference rectangles were isoluminant with their 50% gray surrounds. All 16 subjects made matches to two isoluminant 50% gray test rectangles, shown by the gray squares connected with solid lines. The luminances of these gray matches were essentially the same whether or not subjects simultaneously adjusted chromaticity, as shown by the two virtually superimposed curves. Eight of 16 subjects made matches to isoluminant cyan and gold reference rectangles, and the other eight made matches to isoluminant purple and green reference rectangles. The matches to the colored reference rectangles are represented by the gray circles connected by broken lines.

underlying luminance and chromatic mechanisms. In particular, it weighs heavily against models of color appearance based on contrasts within cone channels, as the achromatic surround generated much higher cone contrasts than the isoluminant surround, but had a weaker influence on the perceived colors of the chromatic rectangles. The gamut expansion effect apparently occurs at or beyond the level of an opponent transformation. (These separable luminance and chromatic effects also tend to validate that the effects of our approximately isoluminant surrounds did not arise from residual luminance errors, as such luminance artifacts could not be expected to specifically affect the chroma-ticity gamut.)

All the surrounds had the identical space-averaged chromaticity and luminance, and differed only in their variances around that mean. The chromaticities of the matches were not significantly biased by the colored surrounds; that is, the achromatic point was not shifted toward cyan, gold, purple or green. The luminances of the matches, on the other hand, were biased by the colored surrounds, as shown in Figure 4. The 50% gray rectangles in the gray surrounds required matching gray rectangles to have approximately 25% higher luminance in the fully colored and achromatic surrounds, and the white and black rectangles were expanded about this higher intensity mid-gray point. The four chromatically colored reference rectangles, although they were isoluminant with the 50% gray rectangles in the gray surround, required matching colored rectangles to have approximately 50% higher luminance in the fully colored and achromatic surrounds. This surprising greater luminance bias for colored rectangles than for equiluminant gray rectangles suggests that subjects were matching appearances on the basis of brightness, not luminance, as chromatic colors appear brighter than equiluminant grays. The isoluminant surround generated only a relatively small luminance bias. Interestingly, the luminance bias made rectangles in the fully colored and achromatic surrounds appear darker than physically identical rectangles in the uniform 50% gray surround, more suggestive of an expansive nonlinearity than the compressive nonlinearity typically associated with early visual processes [11–14]. This may at least partly reflect the viewing conditions, in which the stimuli provided the only lights in an otherwise black room. This luminance bias is also consistent with the hypothesis that the brightest regions in a surround have disproportionately strong influences on color appearance [15–17].

Conclusions

The results clearly demonstrate that color appearance depends on the variance as well as the mean of surround colors. This new form of color contrast was not predicted by leading theories of color appearance and color constancy, and is in fact inconsistent with most of these formulations. It indicates that the effects of complex surrounds on color appearance cannot be reduced to the simpler problem of a homogeneous equivalent surround. The distribution of individual colors constituting the surround has an essential role. We note that any early visual nonlinearities, at or prior to the level of contrast interactions, would be expected to invalidate theories predicting the equivalence of surrounds with equal means. The limited impact of the grout in the first experiment indicates that this cannot be a strictly local interaction at the immediate edges of stimuli. The double dissociation of the effects of luminance and chromatic variances found in the second experiment further indicates that these effects involve processes at or beyond the opponent transformation of cone signals.

Several groups of researchers have identified mechanisms of temporal contrast adaptation, which reduces contrast sensitivity after viewing high-contrast gratings [18] or after adapting to spatially uniform heterochromatic flicker for a few minutes [19–20]. In the present experiments, subjects alternately viewed the experimental and reference displays, raising the possibility of a role for temporal contrast adaptation to each display, as the subjects' eye movements across the display transduced the spatial variance of the displays into retinally local, temporal variance [21,22]. However, our informal observation was that these gamut compression effects were observed almost immediately upon switching between a uniform gray surround and a high-contrast colored surround, inconsistent with slow adapation processes with time constants greater than 1 sec. Moreover, in an earlier version of the present experiment, when subjects performed asymmetric matches of test rectangles between simultaneously presented side-by-side displays, essentially the same pattern of results was obtained, including the dissociation of luminance and chromatic effects and the expansive luminance bias [23]. Thus we conclude that the present phenomenon is effectively a form of simultaneous color contrast, although the precise temporal dynamics of the underlying mechanism remains to be determined. Other psychophysical phenomena which may be closely related to the present effect include simultaneous contrast of perceived texture contrasts [24,25], the 'crispening effect', in which low-contrast edge signals contribute disproportionately to perceived contrast [26,27], and the lightness constancy reported in the presence of additive veiling light [28].

This phenomenon is not predicted by the major classes of color constancy theories, which generally aim to account for color constancy with respect to changes in the intensity or spectral power distribution of the illuminant. Because the present effect depends on changes in the distribution of surround colors, but not the mean light from the surround, it cannot be explained by models based on adaptation to the illuminant or to the mean light signals from scenes [7–9,29]. The double dissociation we found between the effects of luminance and chromatic variance further rule out models based on independent adaptation within cone pathways [4–6,30].

Although this mechanism can lead to failures of color constancy in cases such as that shown in Figure 1, in which physically identical rectangles fail to generate identical color perceptions because of induction from their different surrounds, it is likely to contribute to color constancy under natural viewing conditions that affect contrast. Such conditions include vision through fog, haze or water [23]; indeed, the appearance of our low-contrast displays often had the phenomenological quality of rich colors seen through a thick fog. It has long been understood that perceived colors depend on atmospheric viewing conditions as well as on surface and illuminant properties [1,31], although the modern color constancy literature has largely overlooked these atmospheric effects. Reduced chromatic contrasts may also arise from changes in the bandwidths of illuminants [21,32]. The gamut expansion effect may be adaptive in such instances and perhaps accounts for the surprisingly large gamut of colors perceived under nearly monochromatic illumination by sodium lamps plus small amounts of white light [33]. Another interesting possibility is that this mechanism tends to preserve a relatively large gamut of perceived colors as the neural contrast signals, but not the physical contrasts, are reduced in dwindling light.

Materials and methods

Stimuli were generated by a Number Nine graphics coprocessor board in a 386 PC, and displayed on a Tektronix 690SR color monitor, carefully calibrated using independent linearizing look-up tables for each gun [34]. Additivity errors from interactions between the electron guns were determined to be less than 1%, as previously found for this monitor [35]. The resolution of the display was 640×480 pixels, refreshed at 60 Hz noninterlaced. The mean luminance of the display was 59 cd m^{-2} for all surrounds in experiment 1 and 29 cd m^{-2} for all surrounds in experiment 2. The darker mean luminance was necessary in experiment 2 to achieve the isoluminant surround with saturated colors. The mean chromaticity, in CIE (Commission Internationale de l'Eclairage) x,y coordinates was approximately 0.310, 0.316 for all surrounds in both experiments.

Twenty-eight naive subjects, who 'volunteered' from the UCSD Psychology Undergraduate Subject Pool to obtain course credits, were used in the two experiments. All subjects had approximately normal color vision, as determined by screening with Ishihara plates. Twelve subjects were used in experiment 1, and 16 subjects, randomly assigned to two groups of eight, were used in experiment 2. Each experimental session lasted approximately 40 min.

Subjects sat 1 m from the display, in an otherwise completely dark room, and used a trackball mouse to adjust the colors of the test rectangles in one (experiment 1) or two (experiment 2) dimensions. Subjects pushed mouse buttons to switch back and forth between reference and test surrounds, to select individual test rectangles for adjustment and finally to signal when they had achieved matches for all six rectangles. For each surround condition, subjects were allowed as much time as they wished to achieve simultaneous optimal matches for all six rectangles. A uniform black field was displayed for 3 sec each time surrounds changed, in order to reduce the temporal interactions between surround conditions while minimizing memory demands.

The richly colored surround comprised 131 squares, as illustrated in Figure 1a. Each of the six embedded rectangles was bordered by an identical set of 10 richly colored squares, whose mean was 50% gray, to eliminate possible artifacts arising from random variations in local contrasts. These 10 border squares spanned the monitor's gamut, and included black and white (0 and 120 cd m^{-2}) plus highly saturated colors. The colors of the remaining 71 squares were randomly generated from uniform distributions for each RGB channel, and their mean statistically approximated 50% gray. The gray surround was always a uniform 50% gray. At the subjects' 1 m viewing distance, the rectangles subtended 1×2, the squares 1×1 and the whole stimulus array 13×11 degrees of visual angle. In the 'grout' condition of experiment 1, the array of squares and rectangles was overlaid with thin (8 min of visual angle) strips of 50% gray separating all the squares from each other and from the rectangles, so that all colors in the display were locally surrounded by 50% gray.

The luminances and chromaticities of the reference rectangles to be matched in the first experiment were: 50% gray, 59 cd m^{-2}, $x = 0.310$, $y = 0.315$; white, 65, 0.310, 0.316; black, 52, 0.311, 0.314; yellow, 62, 0.322, 0.335; blue, 52, 0.296, 0.293; green, 61, 0.303, 0.327; red, 54, 0.317, 0.304. In the second experiment, the 50% gray was 29 cd m^{-2}, $x = 0.311$, $y = 0.315$; the six rectangles were: white, 33, 0.310, 0.316; black, 25, 0.310, 0.316; gold, 29, 0.327, 0.328; cyan, 29, 0.298, 0.308; green, 29, 0.318, 0.332; purple, 29, 0.305, 0.301.

The Tektronix 690SR provides excellent color additivity [35], making it suitable for studies of color induction. We measured the precise light signals produced by the monitor using a Photo Research PR-650 Spectra-Colorimeter and verified that changing the surrounds had negligible effects on the color signals emitted by this monitor from each stimulus rectangle, so that our effects must arise in the visual system. The mean colorimetric error in the test rectangles due to changing the surround from uniform 50% gray to fully colored, was 0.21 expressed in ΔE^*_{uv}. ($\Delta E^*_{uv} < 1.0$ is generally considered unimportant.) For comparison, the colored rectangles differed from the gray background by a mean ΔE^*_{uv} of 9.8 and for each of the test rectangles the gamut expansion effect due to changing surrounds was at least 20 times larger than its corresponding monitor colorimetric error.

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