Chromatic variations suppress suprathreshold brightness variations

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Most objects in natural scenes are suprathreshold in both color (chromatic) and luminance contrast. How salient is each dimension? We have developed a novel method employing a stimulus similar to that used by B. C. Regan and J. D. Mollon (1997) who studied the relative saliencies of the two chromatic cardinal directions. Our stimuli consist of left- and right-oblique modulations of color and/or luminance defined within a lattice of circles. In the “separated” condition, the two modulations were presented separately as forced-choice pairs, and the task was to indicate which was more salient. In the “combined” condition, the two orthogonal-in-orientation modulations were added, and the task was to indicate the more salient orientation. The ratio of color to luminance contrast at the PSE was calculated for both conditions. Across color directions, 48% more luminance contrast relative to color contrast was required to achieve a PSE in the “combined” compared to the “separated” condition. A second experiment showed that the PSE difference was due to the luminance being masked by the color, rather than due to superior color grouping. We conclude that suprathreshold brightness variations are masked by suprathreshold color variations.

Keywords: color vision, contrast gain, masking


Introduction

Most objects in the natural visual world are defined by suprathreshold differences in both color (chromatic) and luminance contrast. Although much is known about how these dimensions interact when one of them is at threshold (see below), little is known about how color and luminance saliencies interact when both are suprathreshold.

Previous studies relevant to this issue are of two types. One type of study has considered how the color of a light determines its brightness and whether the brightnesses of different colored lights linearly add when combined (e.g., Booker, 1981; Burns, Smith, Pokorny, & Elsner, 1982; Kaiser & Wyszecki, 1978). These studies have shown that saturated lights tend to appear brighter than equiluminant white lights and that the brightnesses of different colored lights tend not to add linearly when combined. However, the lights used in these studies were equiluminant, and so it is difficult to glean from these studies exactly how the perceived contrasts of suprathreshold luminance variations are affected by the addition of suprathreshold color variations and vice versa.

More germane to the issue are studies that have considered how suprathreshold color and luminance contrasts interact to determine the visibility of edges (Frome, Buck, & Boynton, 1981), and how suprathreshold color and luminance masks, or “pedestals” affect the detection of targets of the other contrast dimension (e.g., Chaparro, Stromeyer, Kronauer, & Eskew, 1994; Chen, Foley, & Brainard, 2000a, 2000b; Cole, Stromeyer, & Kronauer, 1990; Gur & Akri, 1992; Mullen & Losada, 1994; Switkes, Bradley, & De Valois, 1988). Frome et al. (1981) found that color and luminance contrasts contributed independently to determine the visibility of a border (border visibility was defined as the reciprocal of the time taken for the border to fade with fixation). Two findings have emerged from the masking of target studies. First, the majority of the studies have shown that when the mask is low contrast, the detection of the other dimension test is unaffected, and this has been interpreted as showing that
color and luminance detection mechanisms are independent at threshold. Second, when the mask is of high contrast, other dimension target detection thresholds are elevated, but not equally. Chen et al. (2000a, 2000b) and Switkes et al. (1988) found that high-contrast color masks elevated thresholds for luminance targets more than high-contrast luminance masks elevated thresholds for color targets. Chen et al. (2000b) modeled this anisotropy in terms of a difference in the strength of the divisive inhibition exerted by the color and luminance masks.

Paradoxically, the masking of luminance by high-contrast color, as revealed in the studies of Chen et al. (2000a, 2000b) and Switkes et al. (1988), does not inevitably result in elevated luminance detection thresholds. Kingdom and Kasrai (2006) found that for a luminance target placed on a larger Mondrian-like luminance background, target detection improved when color variations were added to the background. Kingdom and Kasrai (2006) suggested that the color variations suppressed the background luminance variations, thus reducing the background luminance noise that limited the detection of the luminance target. They interpreted this result in terms of the wider functional role of color vision in natural scenes. Color variations are more reliable indicators of material changes than are luminance variations; whereas most color variations arise from changes in material, luminance variations arise either from changes in material or from changes in local illumination such as from shadows (Johnson, Kingdom, & Baker, 2005; Kingdom, 2003, 2008; Olmos & Kingdom, 2004; Rubin & Richards, 1982; Shevell & Kingdom, 2008). Kingdom and Kasrai argued that it would make sense for the visual system to suppress luminance variations that are aligned with color variations, in order to facilitate the segregation of the scene into its material and illumination components.

As yet however, there is no direct evidence that color variations mask the saliences of suprathreshold luminance variations, as Kingdom and Kasrai (2006) suggested they do, and which the masking studies of Chen et al. (2000a, 2000b) and Switkes et al. (1988) could be taken to imply. It does not follow however from the finding that color variations mask the detection of luminance targets that the apparent contrast of a suprathreshold luminance target will be similarly masked. Thresholds are determined by other factors besides divisive inhibition, such as levels of internal noise, and internal noise levels are unlikely to influence the magnitudes of perceived contrast.

Intuitively, one might consider “hetero-chromatic brightness-contrast matching” to be the best method to examine whether suprathreshold color variations mask suprathreshold luminance variations. For example, subjects could adjust the contrast of a luminance grating to match the perceived contrast of a test luminance grating to which a color grating had been added, and the difference in contrast between the test and match luminance gratings at the point of subjective equality, or PSE, obtained. However, it is widely recognized that hetero-chromatic brightness matching with patches is a difficult task, and our own observations with grating stimuli confirms that hetero-chromatic contrast matching is also difficult. Therefore, we have developed an alternative method for determining the relative saliences of suprathreshold color and luminance contrasts when the two are combined. Our method involves a stimulus similar to that employed by Regan and Mollon (1997), who compared the saliences of the two chromatic cardinal axes of MacLeod and Boynton’s (1979) color space (see also Mollon, 1999).

The stimuli are illustrated in Figures 1 and 2. Each pattern comprises an array of circular patches filled with color/luminances to form left-oblique, right-oblique, or both left- and right-oblique modulations of color and/or luminance contrast. The patterns are either modulations of color or luminance contrast, termed “component” modulations, or modulations of color and luminance contrast, termed “combined” modulations. Sample component modulations are shown in the top of Figure 1 and in Figure 2, while a single sample of a combined modulation is shown at the bottom of Figure 1. The novel aspect of our method is that we not only measure equate the relative saliences of the color and luminance modulations when combined (i.e., as did Regan & Mollon, 1997 for color-versus-color modulations), but also when presented individually as components. Thus there are two conditions. In the “separated” condition, the color and luminance components, for example the red–cyan (color) and black–white (luminance) patterns in the upper panel of Figure 1, are presented as forced-choice pairs with various ratios of color-to-luminance contrast, and the subject decides on each trial which pattern is more “salient”, meaning having the higher perceived contrast. A point of subjective equality (PSE) is estimated from the resulting psychometric function. In the second “combined” condition, the color and luminance components are made orthogonal in orientation and combined to form a single pattern, as shown in the lower panel of Figure 1. With the combined stimulus, the subject’s task is to decide on each trial whether the dominant perceptual organization is left- or right-oblique. The same set of contrasts is used in the combined as in the separated conditions, and the PSE (defined this time as the relative color-to-luminance contrast at which the left- and right-oblique orientations are equally salient) is again measured.

Subjects appear to find both these tasks easy. One might have expected the separated condition to be difficult, given that subjects are comparing the saliences of two different dimensions—color and luminance contrast. However, Switkes (2008) and Switkes and Crognale (1999) have already shown that subjects are able to reliably and lawfully match the saliences of suprathreshold gratings defined along very different directions of color space, so the ease with which our subjects find the task should not be surprising.

The question we ask is whether the PSEs are different for the “separated” and “combined” conditions. If they
are, this indicates that there must be an imbalance in the saliencies of suprathreshold color and luminance contrasts when the two are combined.

Methods

Subjects

Six subjects participated. FK, JB, and EG were authors, while SM, AM, and LC were volunteers who were naive as to the purpose of the experiment. All observers had normal or corrected-to-normal visual acuity and normal color vision.

Stimuli—generation and display

The stimuli were generated by a VISAGE graphics card (Cambridge Research Systems) and displayed on a Sony Trinitron F500 flat-screen monitor. The R (red), G (green), and B (blue) gun outputs of the monitor were gamma-corrected after calibration with an Optical photometer (Cambridge Research Systems). The spectral emission

Figure 1. Sample (a) red–cyan and (b) black–white component patterns, whose modulations are opposite in orientation, and (c) the two combined.
functions of the R, G, and B phosphors were measured using a PR 640 spectral radiometer (Photo Research), with the monitor screen filled with red, green, or blue at maximum luminance. The CIE coordinates of the monitors’ phosphors were R: x = 0.624, y = 0.341; G: x = 0.293, y = 0.609; B: x = 0.148, y = 0.075.

In both the “separated” and “combined” conditions (see below), the two component patterns were generated on separate pages of the VISAGE’s video memory, along with their own look-up tables (LUTs). During stimulus presentation, the two video pages (and corresponding LUTs) were alternated at the monitor frame rate of 120 Hz, resulting in a stimulus refresh rate of 60 Hz. For the “separated” condition, each component frame alternated with a blank screen, whereas in the “combined” condition the two component frames alternated with each other. This method of display ensured that in the “combined” condition there were no within-frame interactions between
the components, and that any measured interactions were of perceptual origin. The method of frame alternation meant that the contrasts of the components in both “separated” and “combined” conditions were half of that specified in the stimulus generation program and are reported as such below.

Stimuli—lattice pattern

Sample stimuli are shown in Figures 1 and 2. The diameter of the pattern was 3.7 deg at the viewing distance of 110 cm. There were 11 circles along the oblique diameter and 9 circles along the horizontal and vertical diameters. The circles were arranged such that their nearest neighbors lay along the oblique axes. Each circle had a diameter of 0.197 deg. The separation between circles was 0.347 deg along either oblique axis, and 0.49 deg along the horizontal and vertical axes. All circles were ringed by a 1-pixel-wide black line. The ring helped remove any impressions of transparency in the circles were arranged such that their nearest neighbors lay along the oblique axes. Each circle had a diameter of 0.197 deg. The separation between circles was 0.347 deg along either oblique axis, and 0.49 deg along the horizontal and vertical axes. All circles were ringed by a 1-pixel-wide black line. The ring helped remove any impressions of transparency in the combined condition and mask any chromatic aberrations at the edges of the circles in the color conditions.

Stimuli—colors

Each component pattern comprised two colors defined as points straddling the midpoint of an axis in a modified version of the MacLeod–Boydton (MB) color space (MacLeod & Boynton, 1979). The isoluminant plane of the MB color space is illustrated in Figure 2c and shows the two major, or “cardinal”, as well as intermediate chromatic axes. The luminance axis, which is orthogonal to the isoluminant plane, is not shown. In this version of the MB color space, points are defined by combinations of long-wavelength-sensitive (L), middle-wavelength-sensitive (M), and short-wavelength-sensitive (S) cone contrasts. The three cone contrasts are defined as: $L_c = \Delta L/\Delta \lambda_L$, $M_c = \Delta M/\Delta \lambda_M$, and $S_c = \Delta S/\Delta \lambda_S$ (Cole, Hine, & McIlhagga, 1993; Norlander & Koenderink, 1983; Sankeralli & Mullen, 1997; Stromeyer et al., 1985). The denominator in each cone contrast term refers to the cone excitation produced by the background, which was a mid-gray color with CIE chromaticity of $x = 0.282$ and $y = 0.311$ and luminance of 40 cd/m². The numerator in each cone contrast term represents the difference in cone excitation between the circle test color and the background. The LMS cone excitations assigned to each circle and background were converted to RGB phosphor intensities using the cone spectral sensitivity functions provided by Smith and Pokorny (1975) and the measured RGB spectral functions of the monitor.

Three of the five types of component patterns are defined along the three cardinal axes, termed here “S”, “L–M” (Figure 2c), and “LUM” (not shown), which stands for luminance. The term “cardinal” implies that the colors uniquely stimulate one of the three post-receptoral mechanisms (Cole et al., 1993; Derrington, Krauskopf, & Lennie, 1984; Krauskopf, Williams, & Heeley, 1982; Norlander & Koenderink, 1983; Sankeralli & Mullen, 1997; Stromeyer et al., 1985). The relative cone contrast inputs to the three post-receptoral mechanisms have been estimated to be as follows: $kL_c + M_c$ for the luminance mechanism, $L_c - M_c$ for the mechanism that differences L and M cone contrasts, and $S_c = (L_c + M_c)/2$ for the mechanism that differences S from the sum of L and M cone contrasts (Cole et al., 1993; Sankeralli & Mullen, 1997; Stromeyer et al., 1985). The parameter $k$ determines the relative weightings of the L and M cone contrast inputs to the luminance mechanism, varies between observers, and was established for each subject (see below). In order to isolate the three cardinal mechanisms from each other, the stimuli must be constructed such that the L–M stimulus does not activate either the LUM or the S mechanism, the S stimulus neither the LUM nor L–M mechanism, and the LUM stimulus neither the S nor L–M mechanism. Kingdom, Rangwala, and Hammanji (2005) used the following combinations of $L_c$, $M_c$, and $S_c$ to achieve this:

\begin{align}
\text{‘LUM’} &= L_c + M_c + S_c, \\
\text{‘L–M’} &= L_c - kM_c + S_c(1 - k)/2, \\
\text{‘S’} &= S_c.
\end{align}

In addition to the LUM, L–M, and S color pairs, we also constructed patterns defined by pairs of colors along the axes intermediate to the chromatic cardinal axes, which we term “S + (L–M)” and “S − (L–M)”. To assist the reader, we refer to the five types of component patterns also by their (approximate) hues: “red–cyan” for L–M, “violet–chartreuse” for S, “purple–green” for S + (L + M), “blue–orange” for S − (L–M), and “black–white” for LUM (see Figures 1 and 2).

The measures of contrast reported in Table 1 were calculated as follows: for LUM, the contrast assigned to each of the three cones (i.e., $L_c = M_c = S_c$); for L–M, the difference between $L_c$ and $M_c$; for S, simply $S_c$. For the intermediate S + (L–M) (purple) and S − (L–M) (blue–orange) colors, the S contrast is given in Table 1, and the L–M contrasts are calculated by multiplying the S contrast by a factor $m$ that equated the perceived S and L–M contrasts and was determined for each subject from the results of the “separated” S and L–M color direction.
conditions. The value of $m$, which equates the perceived contrasts of the S and L–M contrasts in the purple–green and blue–orange color stimuli, was determined for each observer to be JB = 0.198, SM = 0.189, and FK = 0.222.

Note that for the L–M and LUM contrasts there is an additional low contrast condition. This was to test for the generality of any result across contrast. Note also that whereas data for all color directions and contrasts was gathered for subjects JB, FK, and SM, only data for the red–cyan color direction were obtained for AM (a naive subject) and EG (an author). Subjects AM and EG were tested on only one condition to test the generality across subjects of the main finding of the study.

Procedure—measurement of isoluminance

Because of inter-subject variation in the relative weightings of the L and M cones that feed the luminance mechanism, it was necessary to ensure that the colors combining L and M cone modulations were isoluminant (S cones have a negligible input to the luminance mechanism; Eskew, McLellan, & Giulianini, 1999). We used the criterion of minimum perceived motion. A 0.025 contrast, 0.5 cpd L–M (red–cyan) sinusoidal grating was set to drift at about 1.0 Hz. Subjects pressed a key to add or subtract luminance contrast to the grating until the perceived motion was at a minimum. Each subject made between 20 and 30 settings. The average amount of luminance contrast added (or subtracted) was used to calculate the parameter $k$ in Equation 1b, which is the ratio of $L_c$ to $M_c$ in the putative luminance mechanism.

For the six subjects, $k$ was determined to be: JB = 0.87, SM = 0.74, FK = 1.7, AM = 1.2, EG = 1.63, and LC = 1.75.

Procedure—“separated” condition

In this condition, the two components were presented separately to the observer on each trial using a two-interval forced-choice (2IFC) procedure. A sample pair of components is shown in the top of Figure 1. The task for the subject was to indicate by a key press the interval containing the more salient stimulus. It was explained to the subject that “more salient” was synonymous with “higher perceived contrast”. Each stimulus was presented for 500 ms with an inter-stimulus interval of 500 ms. Trials were initiated by the previous key press, with an interval of 500 ms before the onset of the first stimulus. During each session, 8 ratios of the contrasts of the two components were presented in random order, with 20 trials per ratio, making a total of 160 trials per session. The contrast of each component was selected from 8 logarithmically spaced values with a given range and geometric mean. The contrast ratios between component pairs were chosen such that the geometric mean contrast ratio of the two
components was a constant. Thus if the contrasts were indexed a1 to a8 for one component and b1 to b8 for the other, the pairings would be a1 and b8; a2 and b7; a3 and b6; a4 and b5; a5 and b4; a6 and b3; a7 and b2; a8 and b1. The contrasts of each component were selected on the basis of pilot data to ensure that the proportion of responses ranged approximately from “0” to “1”. Full details of the ranges and geometric means of the contrasts for all conditions are provided in Table 1.

**Procedure—“combined” condition**

In the “combined” condition, the two components were added together. The same set of contrasts and contrast ratios were employed as in the “separated” condition. On each trial, the stimulus was presented for 500 ms and a single key press indicated the orientation, left- or right-oblique, that was more salient. After the response, there was a 500-ms inter-trial interval before the next stimulus was presented. As with the separated condition, there were 160 trials per session.

**Data analysis**

Psychometric functions were fitted and analyzed using the Palamedes toolbox (Prins & Kingdom, 2009). The data were fitted with the Logistic function

$$F_L(x; \alpha, \beta) = \frac{1}{1 + \exp(-\beta(x - \alpha))},$$

where \(x\) is the log (logarithm) ratio of component contrasts, \(\alpha\) is the PSE defined as the ratio producing a proportion of 0.5 responses, and \(\beta\) is the slope of the function. The fitting procedure used a maximum likelihood criterion and the errors on the PSE and slope parameters were estimated by parametric bootstrap analysis. Any differences in the PSE and slope estimates between the “separated” and “combined” data were tested for statistical significance using the likelihood ratio test in Palamedes (for an explanation of this test, see Kingdom & Prins, 2010).

**Results**

Figure 3 shows the complete set of psychometric functions for subject SM, who was naive as to the purpose of the experiment. Each graph plots the proportion of times one component was chosen as more salient than the other as a function of the log (logarithm) contrast ratio of the two components. The green and indigo lines are best fits for the “separated” and “combined” conditions, respectively. PSEs are calculated as the log contrast ratio on the abscissa at the 0.5 level on the ordinate. Note that for the red–cyan versus black–white condition results for two contrast levels are presented (see Table 1 for details). In all graphs, the “combined” psychometric function falls to the left of the “separated” psychometric, and the difference in PSE estimates between the two functions is in all cases highly significant \((p < 0.001)\). The direction of the shift reveals that more luminance contrast relative to color contrast is needed to achieve the PSE in the “combined” compared to “separated” condition.

Figure 4 shows the PSE estimates for all subjects and all conditions. Raw rather than log contrast ratios are shown on the ordinates, albeit spaced logarithmically. As can be seen, for all subjects and all color directions, PSEs are higher for the “separated” compared to “combined” conditions, and the difference is in every case highly significant \((p < 0.001)\). The data therefore show throughout that more luminance contrast relative to color contrast is needed to achieve the PSE in the “combined” compared to “separated” conditions. Red–cyan data for three additional subjects (AM, EG, and LC) are shown to test for between-subject reliability in the main result.

To compare results across different color directions and contrast, we first calculated the difference in PSE between separated and combined conditions for the three subjects who performed all conditions: JB, FK, and SM. A within-subjects one-way ANOVA (analysis of variance) with Color Direction as a factor revealed no significant difference between color directions at the \(p < 0.05\) level \([F(3, 6) = 0.74; p = 0.57]\). To test for any differences between the cardinal and intermediate color directions, we combined the data for the two cardinal and for the two intermediate directions and conducted a within-subjects \(t\)-test but found no significant difference \([t(2) = 1.07; p = 0.4]\). Finally, we found no significant difference between the high and low contrast conditions in the red–cyan versus black–white condition \([t(2) = 0.46; p = 0.69]\).

**Masking or grouping?**

Two possible explanations for the PSE difference spring to mind. The first is that in the combined condition the color modulations mask the luminance modulations. The second is that in the combined condition a competitive grouping process occurs that favors the color modulations and renders them more salient. How might one test between the two explanations? If masking is the reason for the PSE difference, it presumably occurs because the color and luminance contrasts are added together within each circle of the lattice. Therefore, one way to test between the two above explanations is to use a stimulus in which the color and luminance modulations are not added to the same circles but put into different circles.
Figure 5 shows how this can be achieved. In the red–cyan component, a random selection of half of the circles is filled with colors, and in the black–white component, the other circles are filled. Thus when the two components are combined, all the circles are filled, but no circle contains both color and luminance contrasts. We refer to the stimuli in Figure 5 collectively as the “segregated” conditions, in contrast to the “non-segregated” conditions used in the previous experiments. The question is whether the same PSE difference is found with the segregated as with the non-segregated conditions. If it is, this would show that the PSE difference is not contingent on the color and luminance components being together within each circle, and that it is therefore not due to masking but to some other process such as grouping. On the other hand, if the PSE difference disappears in the segregated condition, this would suggest that the results of the main experiment are due to masking not grouping.

We therefore repeated the experiment using the segregated stimuli illustrated in Figure 5. On each trial, a random selection of 50% of circles in one of the components was filled with red–cyan, and the other 50% of circles in the other component were filled with black–white. Data were gathered for the same six subjects that performed the red–cyan versus black–white condition in the main experiment, and the results are shown in Figure 6. The direction of the PSE difference is completely reversed in 5 out of the 6 subjects (compare with the upper left graph in Figure 4). The (reversed) PSE difference is highly significant ($p < 0.001$) in all subjects except the one not showing a reversal, for which the difference was not significant. This means that with the segregated stimuli,
more color relative to luminance is required to balance the modulation saliencies in the combined compared to the separated condition. This suggests that the PSE difference in the main experiment is contingent upon the color and luminance modulations being together within the circles of the lattice, and therefore that masking not grouping is its cause.

**Discussion**

Averaging the results of the main experiment across subjects and color direction, the difference in PSE between the “separated” and “combined” conditions is −0.17 log units, corresponding to a 48% difference. The direction of the PSE difference shows that more luminance contrast relative to color contrast is needed to balance the two modulations in the “combined” compared to “separated” conditions. In terms of the magnitude of this PSE difference, we found no significant differences between different color directions, between cardinal and intermediate color directions, and between low and high contrasts. This suggests that the effect generalizes across color direction and contrast.

In and of itself, the finding does not tell us whether color contrast masks luminance contrast, luminance contrast enhances color contrast, both luminance and color contrasts are masked but the former more than the latter, or both luminance and color contrasts are enhanced but the latter more than the former. However, a brief scrutiny of the “combined” stimuli suggests that neither of the enhancement scenarios is the case: as one might
expect, the colors appear less saturated in the combined compared to separated conditions. Therefore, it is reasonable to conclude that in the main experiment color contrast has a greater masking effect on brightness contrast than does luminance contrast on color contrast, and the discussion that follows starts from this premise.

It might be supposed that the reason why color contrast dominates over luminance contrast in the combined condition is because the background is gray, i.e., achromatic like the black–white component. Perhaps the black–white component pattern blends into the background more than does the color component pattern, and that therefore more black–white contrast is needed to balance the color pattern. The problem with this argument is that it predicts the opposite of what was found; one would expect the black–white component to maximally blend into the background when presented on its own rather than when combined with the color pattern, resulting in relatively more black–white contrast to balance the color contrast in the “separated” compared to “combined” condition.

A second experiment showed that the masking effects of color occurred only when the color and luminance contrasts were added within each circle of the lattice. When the color and luminance contrasts were segregated into different circles, the direction of the PSE difference reversed in 5 out of 6 subjects. In other words, with the
segreated conditions, less luminance contrast was needed to balance the components in the combined compared to separated patterns. This suggests three things. First, the direction of the PSE difference in the main experiment is a result of masking rather than grouping; second, there is a competitive grouping process operating in the combined conditions, but it favors luminance over color; third, the size of the masking effect observed in the main experiment may, if anything, be an underestimate. This third conclusion follows the argument that if the competitive grouping process revealed in the segregated condition also occurs in the main experiment, it will tend to reduce the masking effect of the color because it operates in the opposite direction.

The results from this experiment that lend themselves most directly to comparison with those from previous studies are the results from the separated condition. Switkes and Crognale (1999) and see also Switkes, 2008 matched the saliencies of gratings defined along the LUM, L–M, and S cardinal axes. From a visual inspection of their Figure 3, it appears that the mean contrast matching ratios were approximately 0.6 for L–M matched with LUM and 4.2 for S matched with LUM. If we recalculate the contrasts of our stimuli in terms of the measure used by Switkes and Crognale (1999), who defined contrast as the square root of the sums of squares of the L, M, and S cone contrasts, the mean contrast matching ratios in our “separated” condition are approximately 0.7 for L–M with LUM and 3.0 for S with LUM. Given the difference in the stimuli between the two studies, the measures are surprisingly similar.

The results of the present study are consistent with an oft-noted observation that luminance contrasts are perceptually “dampened” by spatially aligned color contrasts (e.g., Kingdom & Kasrai, 2006). Moreover, as was noted in the Introduction section, Chen et al. (2000a) and Switkes et al. (1988) found that high-contrast color masks elevate thresholds for luminance targets more than high-contrast luminance masks elevate thresholds for color targets, which is consistent with our findings. However, as we stressed in the Introduction section, performance-based threshold measurements and appearance-based salience measurements do not necessarily tap into the same set of visual mechanisms.

There are two important caveats to our assertion that suprathreshold color variations mask suprathreshold luminance variations. Our results were obtained using a particular stimulus, one in which the dominant orientations of the color and luminance components were orthogonal. We do not know therefore whether similar results would be obtained if the color and luminance components were spatially aligned, although it seems reasonable to suppose that they would. The stimulus/task we have employed in this study does not lend itself easily to testing for interactions between spatially aligned suprathreshold color and luminance contrasts, so the effects of spatial alignment must await a different experimental approach.

Our results are congruent with the idea that one of the functional roles of color vision is to signal material changes rather than non-uniform illumination. If those luminance variations that are aligned with color variations are masked by the color variations, as suggested here, this might facilitate the segmentation of the image into its material and non-uniform illumination layers (Kingdom & Kasrai, 2006).

As a final note, one arguable shortcoming of the present study is that we have not explored in detail the interaction between color and luminance contrasts across the full range of color and luminance contrast levels. Although we found no significant difference between the two contrast levels we tested in the red–cyan versus black–white condition, it is possible that significant differences would have emerged had we independently manipulated color and luminance contrasts across the full range of their contrasts. We hope to use the present method to explore in greater detail the contrast dependence of color suppression of brightness in a future study.

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