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Color from motion: separate contributions of chromaticity and luminance

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Abstract. 'Color from motion' describes the perception of a spread of subjective color over achromatic regions seen as moving. The effect is produced with a stimulus display consisting of colored dots, randomly placed upon a white field, with dots in the test region differing in both chromaticity and luminance from those in the surround. Evidence is presented suggesting that color from motion may be regulated by mechanisms different from those for contour formation and color contrast. (1) Results based on ratings show that, in the absence of luminance differences between the dots in the test and those in the surround regions, chromaticity differences alone are sufficient to produce color spread from motion. As the equiluminance point is approached, subjective color spread is seen despite a reduction in the strength of the subjective contour. Thus, contour formation is not likely to be a prerequisite for color from motion. (2) Color matches show that the hue and saturation of the subjective color spread are determined largely by the chromaticity and the luminance of the dots in the test region, not by those of the dots in the surround for the values explored. This suggests that color from motion may arise in sites distinct from those responsible for the regulation of color contrast.

1 Introduction

'Color from motion', introduced by Cicerone et al (1995), describes the perception of a spread of subjective color over physically achromatic regions seen to be moving. Figure 1 (left) shows one frame of a typical display of color from motion. A single frame consists of a white square containing a random array of small, colored regions (called 'dots'). In this example the dots inside a circular test region are green and the dots outside the test region, called the surround, are red. The location of the test region is uniformly displaced from frame to frame by changing the color assignments of the dots without changing the dot locations. Thus, the locations of the dots are the same from one frame to the next, only the chromaticity or luminance, or both, of the dots are changed in the successive test regions. When the stimulus, consisting of twelve such frames, is shown in rapid succession, one sees a moving circular region, colored green throughout, even in the physically achromatic regions seen to be moving (figure 1, right). The moving, colored region is spatially linked to the changes in color or luminance assignment of the test dots. Most observers report a green disk within which lie green dots, all moving over a field of red dots; others report a green disk moving over a field of red dots. Cicerone et al (1995) found that, for slow rates of change in the color of the dots, little or no apparent motion is perceived and the spread of subjective color is not seen. Hence, the effect was called 'color from motion'. For displays such as those shown in figure 1, with both chromaticity and luminance differences in test and surround dots, a clear subjective contour bounding the colored, moving region was seen. The appearance of a subjective contour defined by motion is not new (Sekuler and Levinson 1977; Klymenko and Weisstein 1981; Kellman and Cohen 1984; Peterhans and von der Heydt 1991), nor is the appearance of neon color spreading in static displays (eg Varin 1971; van Tuijl 1975; Redies and Spillmann 1981; Nakayama et al 1990). What is novel in color from motion is the spread of subjective color into physically achromatic regions only when these regions are seen to be moving.

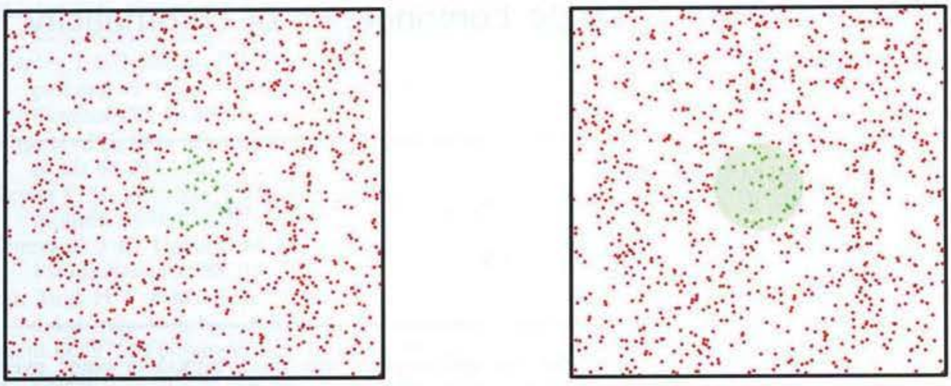

Figure 1. One of the frames of the stimulus is shown in the left panel. A single frame consists of a white square containing a random array of dots. The dots inside a circular test region are of one luminance and chromaticity, green in this example, and the dots outside the circular test region, called the surround, are another combination of luminance and chromaticity, red in the example. The location of the test region is uniformly displaced from frame to frame. Thus, the locations of the dots are the same from one frame to the next, only the chromaticity or luminance, or both, of the dots are changed in the successive frames. When the stimulus, consisting of twelve such frames, is shown in rapid succession, one sees a moving circular region throughout which subjective color spreads into physically achromatic regions (as illustrated in the right panel).

The present study addresses whether the perception of color from motion requires *both* luminance and chromaticity differences between the dots of the test and of the surround, or whether either alone can produce the effect. Although color from motion is a clear and vivid percept, a careful analysis of the effects of luminance and chromaticity requires more than a simple report of the presence or absence of subjective color spread. We used a rating method and a color-matching method devised for this purpose. The results of experiments 1 and 2, involving ratings of apparent motion, color spread, and subjective contour, showed that color from motion was perceived even when the test dots and the surround dots were near equiluminous. As the equiluminance point is approached, subjective color spread is reduced but less so than the reduction in

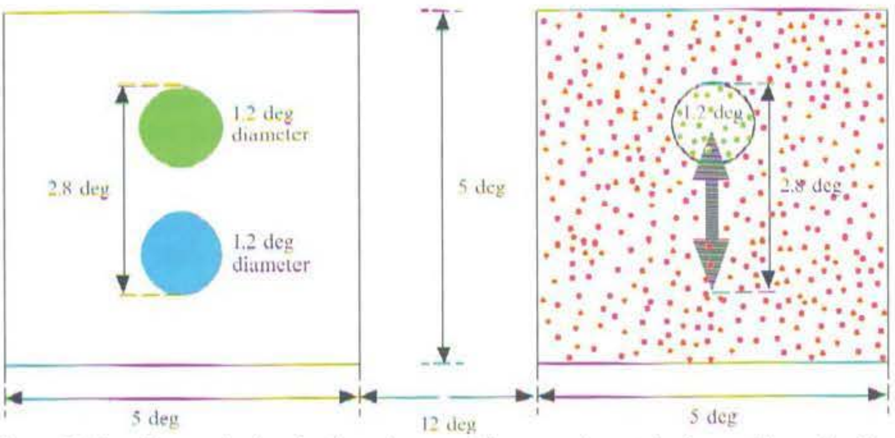

Figure 2. The observer's view in the color-matching experiments is shown. The color-from-motion stimulus (shown at the right) and the color-matching stimuli (shown at the left) were presented on separate monitors. The color-from-motion stimulus is described in section 2.2. The comparison stimuli were presented as two disks (1.2 deg diameter, matching the test region of the color-from-motion stimulus) vertically separated by 0.4 deg within a 5 deg × 5 deg white square. The color-from-motion stimulus was separated by 12 deg from the comparison stimuli. All other details are presented in section 4.2.

strength of the subjective contour. In experiment 2, the observations of a deuteranope were compared with those of color normals to show that, in the absence of chromaticity differences, luminance differences between the test and surround dots are sufficient to produce color from motion. Changes in hue and saturation of the subjective colors were assessed with color matches in experiments 3 and 4. Increases in the luminance of the dots in the test region produced increases in the saturation of the color matches to the subjective colors while leaving hue unchanged. Variations in the luminance of the dots in the surround, for the range of values we tested in experiment 3, had little or no effect on color matches to the subjective colors. Under the conditions of experiment 4, the chromaticity of the dots in the surround region did not affect the hue or saturation of the subjective colors. These results suggest that color from motion may arise in sites distinct from those responsible for the formation of contours and the regulation of color contrast.

2 Experiment 1: Chromaticity differences alone can produce color from motion

2.1 *Introduction*

It should be noted that surround dots are necessary for this effect. In a display lacking dots in the surround region and for which test dots, in an otherwise white background field, are successively displaced according to the same rule used in the standard display, all observers reported the following perception: a white sheet with a moving aperture, defined by a circular contour, through which could be seen an underlying field of static, randomly arrayed colored dots. No subjective color spread was seen. Thus, without the surround dots, apparent motion of a subjective contour is seen, but no subjective color spreading is seen. In the reverse configuration, surround dots without test dots, all observers reported the following perception: a circular, white, or near-white disk moving over a field of colored dots, randomly arranged on a white field. (Perhaps owing to color assimilation, some observers reported that the white disk was tinged by the same hue, highly desaturated, as the dots in the surround.) In this case, the surround produced no change in the uniformly white test region by means of color contrast. However, in a previous study (Cicerone et al 1995) with achromatic test dots of varying luminance and a surround composed of red dots of fixed luminance, observers reported a color change in the test dots, from gray to blue-green, when the stimulus was seen to be moving. Some observers saw the achromatic dots as blue-green even in still view of a single frame with an enhancement of color contrast when apparent motion was seen. This shows that surrounds composed of colored dots can produce color-contrast effects if there are dots in the central test region but not if the test region is a homogeneous white field. Thus, we expected that the chromaticity and luminance of the surround dots as well as of the test dots would play a role in the subjective color spread seen in color from motion.

The purpose of experiment 1 was to explore the role of luminance in the perception of color from motion. In particular, we asked whether apparent motion and color spread would be observed when the test dots and the surround dots were equiluminous and differed only in chromaticity. In this case, we expected that the strength of the subjective contour would be reduced or that it would not be seen at all. Luminance contrast is known to be critical for the formation of static subjective contours (Frisby and Clatworthy 1975; Gregory 1977), the perception of apparent motion (Ramachandran and Gregory 1978; Cavanagh et al 1985), and the perception of achromatic neon spreading (Bressan 1993). If, near equiluminance, color spread occurs without the formation of a subjective contour or with a reduction in its strength, then the mechanisms for subjective color spread in color from motion can be viewed as different from those regulating contour formation.

2.2 *Method*

2.2.1 *Stimuli.* The stimuli were generated by means of a Macintosh IIfx computer and were presented on a RasterOps monitor. The spectral power distributions and luminances of each phosphor were measured with a Photo Research PR-650 spectrocolorimeter. The observer viewed the monitor at a distance of 112 cm. The stimulus consisted of twelve frames and each frame was a white (CIE $x = 0.276$, $y = 0.286$; 67 cd m^{-2}) square (5 deg on each side) containing 900 randomly placed dots. Each dot (3 min arc) was created by using either the green (CIE $x = 0.280$, $y = 0.610$) or the red (CIE $x = 0.621$, $y = 0.344$) phosphor. Figure 3 is a plot of the locations of the red and green phosphors and the screen white in CIE space. In each frame dots falling within a circular region (1.2 deg in diameter) were assigned to the test and were either red (denoted R) or green (denoted G) and of luminance 4, 8, or 16 cd m^{-2}. In the surround region, outside the test region, dots were fixed at 8 cd m^{-2} and were all red or all green. Chromaticity (R or G) and luminance (in cd m^{-2}) combinations for test and surround were R4/G8, R8/G8, R16/G8, G4/R8, G8/R8, G16/R8, R4/R8, R16/R8, G4/G8, and G16/G8. With the dot locations kept fixed, the circular test region was displaced vertically from frame to frame by reassignments of chromaticity and luminance. Presentation of twelve frames in quick succession matched an effective speed of 3.3 deg s^{-1}.

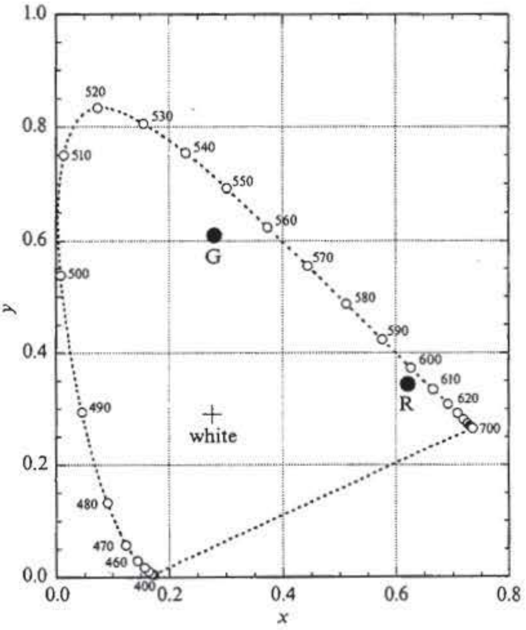

Figure 3. Chromaticity coordinates of test dots, surround dots, and the white background are plotted in CIE space. All dots were either red (CIE $x = 0.621$, $y = 0.344$, denoted by R in the figure) or green (CIE $x = 0.280$, $y = 0.610$, denoted by G in the figure). The background was the screen white (CIE $x = 0.276$, $y = 0.286$; 67 cd m^{-2}). See the methods sections for the specific combinations of luminance and chromaticity of test and surround dots used in each experiment.

2.2.2 *Procedure.* Ten stimuli, varying in luminance and chromaticity of the test and surround dots as described above, were presented in random order. In one session, each of the ten stimuli was presented three times (thirty trials per session). After one practice session, four experimental sessions were run on different days. Neither exact direction of gaze nor steadiness of fixation were critical for the effect. Observers were asked to direct their gaze near the center of the display and asked to make as careful a judgment as possible. We did not track eye movements. On each trial, observers were asked to rate apparent motion, color spreading, and subjective contour on a 5-point scale. Observers were instructed to use the rating 0 if absolutely certain of the absence of the attribute, 1 if moderately certain of the absence of the attribute, 2 if uncertain, 3 if moderately certain of the presence of the attribute, and 4 if absolutely certain of the presence of the attribute. Thus, the presence of an attribute was indicated by a rating greater than 2, its absence by a rating less than 2.

Heterochromatic flicker photometry (HFP) was used to obtain measurements of luminance matches between stimuli created with the red and green phosphors for each observer. Observers viewed a circular field (1 deg in diameter) produced alternately by the red or green phosphor with a temporal alternation rate of 15 Hz. The luminance of the red was fixed at 20.1 cd m^{-2} while observers varied the luminance of the green field using the method of adjustment until flicker was minimized. Two sessions consisting of ten such adjustments were conducted for each observer. The results are shown in table 1. Each observer's equiluminance match fell near the middle of the range of ratios of test-dot/surround-dot luminance we used. There may be a concern that the HFP measurements do not translate into equiluminance for the dots in our stimulus because the dots had a smaller area than the stimulus used for the HFP measurements. This appears not to be important for the purposes of our experiments because all observers judged that the range of test-luminance/surround-luminance conditions spanned the range from clearly below equiluminance to clearly above equiluminance when viewing the experimental stimuli. As described later, a dichromatic observer was used as an added control for testing the effect of luminance on color from motion.

Table 1. Summary of heterochromatic-flicker-photometry measurements. Deviation from photometric values in cd m^{-2} are on a logarithmic scale. Positive numbers mean that the observer is more sensitive to the red stimulus than to the green stimulus and negative numbers vice versa.

	Observer						
	BB	CC	FD	SF	EM	SW	AS[a]
Deviation	0.0955	0.0565	−0.0393	0.0215	0.0388	0.0739	0.1422

[a] Deuteranopic observer.

2.2.3 *Observers.* The observers were six color-normal trichromats as assessed with the Neitz OT anomaloscope (Neitz Instruments Co Ltd, Tokyo). Four of the observers were unaware of the purposes of the experiment.

2.3 *Results and discussion*

The mean results of the six color-normal observers under four conditions are shown in figure 4.

Chromaticity differences between the test dots and the surround dots, in the absence of luminance differences, produced a spread of subjective color from motion (figure 4, top two panels). Moreover, for conditions in which the test dots were of higher luminance than the surround dots, ratings of perceived color spread were greater than for conditions with test and surround dots equiluminous, suggesting that greater test-dot luminance can enhance the effect. For conditions in which the test dots were less luminous than the surround dots, the average ratings of apparent motion were significantly greater than 2 (neutral rating value) whereas the average ratings of the spread of subjective color were not significantly different from a rating of 2. That apparent motion can be seen without the spread of subjective colour under these conditions is added evidence for the idea (Cicerone et al 1995) that apparent motion must be perceived before subjective color spread can be perceived. As test dot luminance is decreased and the equiluminance point is approached, subjective color spread is

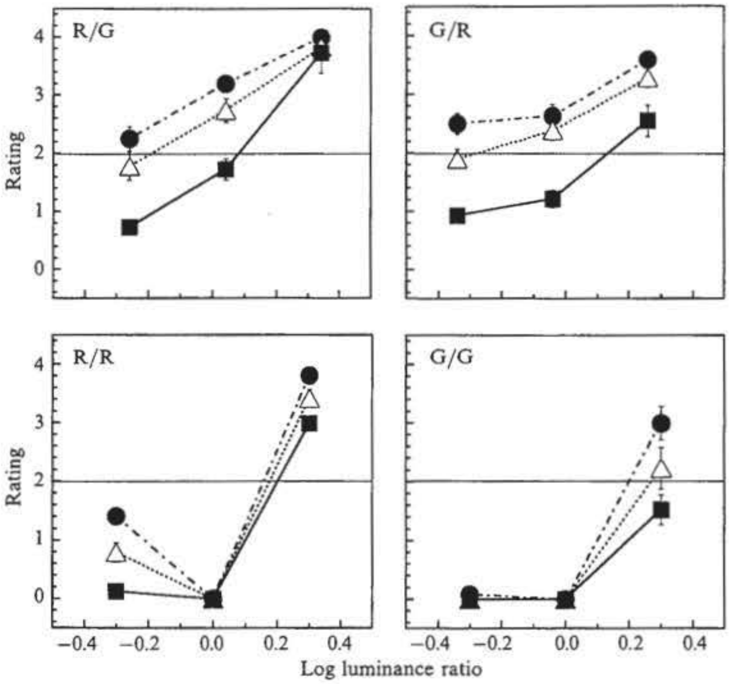

Figure 4. Mean ratings for six observers for apparent motion (solid circles), color spread (open triangles), and subjective contour (solid squares) are shown as a function of the logarithm of the luminance ratio of test dots to surround dots. The horizontal line marks the rating 2, "uncertain of the presence or absence of the attribute". Ratings above the line indicate presence of the attribute, below the line indicate absence. Error bars indicate standard errors of the mean over observers. The upper-left panel shows the ratings for the condition with the red test and green surround, the upper-right panel for the green test and red surround, the lower-left panel for the red test and red surround, and the lower-right panel for the green test and green surround. All plotted mean luminance values are based on averages of the observers' heterochromatic-flicker-photometry (HFP) measurements (table 1). The standard errors of the mean among the observers for HFP were smaller than the size of the symbols. When the test dots and the surround dots were of the same chromaticity and luminance, we plotted rating values of zero (lower panels).

reduced but there is a larger reduction in strength of the subjective contour. Thus, in these conditions observers see the spread of subjective color without seeing a distinct subjective contour, suggesting that color spread and the formation of a subjective contour are governed by separate mechanisms. This is parallel to findings which show that color spread and contour formation in the static neon color display are governed by separate mechanisms (Grossberg and Mingolla 1985a, 1985b; Grossberg 1987; Watanabe and Sato 1989).

For conditions with test and surround dots of the same chromaticity (both red or both green) and of different luminances, color spread was perceived if the test dots were more luminous than the surround dots but not when the test dots were less luminous than the surround dots (figure 4, bottom two panels). Such an asymmetry could arise if the measurements had not included the equiluminance point. That the range of values we used included the equiluminance point was confirmed for each observer with HFP measurements (table 1 and section 2.2) and with the experimental stimuli. Thus, the reason for the asymmetry is unexplained by these results.

3 Experiment 2: Ratings of apparent motion, color spread, and subjective contour by a dichromatic observer

3.1 *Introduction*

Another way to study the role of luminance differences is to use red–green dichromatic observers who are incapable of making red–green discriminations on the basis of chromaticity differences alone. In experiment 2 we measured observations by a deuteranope. The deuteranope lacks the middle-wavelength-sensitive pigment and is therefore insensitive to chromaticity differences in the middle-wavelength to long-wavelength region of the spectrum. In this part of the spectrum—where the color normal has two pigments and sees differences in redness and greenness as well as differences in luminance—the deuteranope sees only luminance differences, based on the activity of the long-wavelength-sensitive cones (Dalton 1798; Judd 1948; Jameson and Hurvich 1955). Thus, the results from a red–green dichromat should allow us to assess, in isolation, the impact of luminance differences in these stimuli. Furthermore, a comparison of the results of the color-normal observers against those of the deuteranope allows an assessment of the separate effects of luminance as compared with chromaticity in the results of the color-normal trichromats.

3.2 *Method*

The methods were the same as in experiment 1, except for the following: (i) observer AS was a deuteranope as assessed by the Neitz OT anomaloscope; (ii) given his lower sensitivity to stimuli produced by the green phosphor as compared with the red, as shown in his HFP measurements (table 1), we added another luminance combination in order to match the range for color normals.

3.3 *Results and discussion*

The average results of the six normal trichromats are compared with those of the deuteranope in figure 5. We show results for three conditions: red test, green surround; green test, red surround; and red test, red surround. The results for the condition with green test and green surround are not shown because they were essentially identical to those for the red test combined with the red surround.

As shown in experiment 1, normal trichromats perceived apparent motion and color spreading even when the test and the surround dots were near equiluminance, as long as the test and the surround were of different chromaticities. In contrast, the deuteranope's results (figure 5, lower panels) showed no effect at equiluminance for all three conditions, including the conditions with chromaticity differences. The comparison, between the results of normals and the deuteranope for stimuli with little or no luminance variations, provides additional evidence that at equiluminance chromaticity difference alone can produce the spread of subjective color over regions seen to be moving for color-normal observers. Increasing the luminance of the test dots as compared with that of the surround dots enhances the spread of subjective color both for color-normal observers and for the deuteranope, as indicated by the higher ratings.

4 Experiment 3: Greater luminance of test dots enhances the saturation of perceived color from motion

4.1 *Introduction*

The results of experiments 1 and 2 show that, in the absence of luminance differences in the test and surround dots, chromaticity differences alone can produce color from motion for color-normal observers. The results shown in figures 4 and 5 also show that increasing the luminance ratio between test dots and surround dots enhances the perceived color spread as measured by the observers' mean ratings. The rating method provides a qualitative estimate of color spread, without giving a measure of changes in

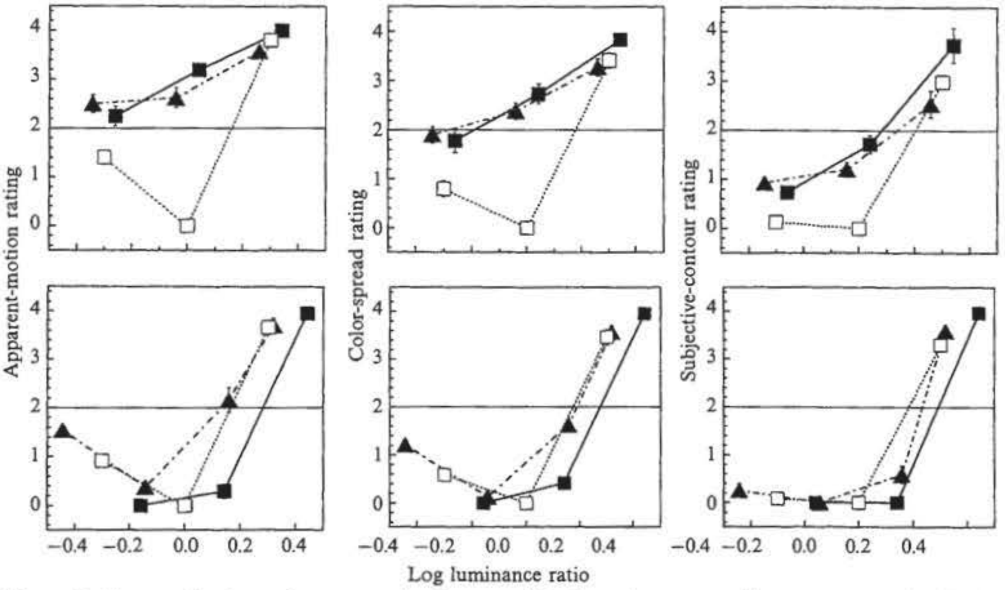

Figure 5. The results for a deuteranopic observer AS (three lower panels) are compared with the mean results for the six normal trichromats (three upper panels). In order to make the comparisons between color-normal observers and the deuteranope more readily, we plot separately the ratings of apparent motion (left two panels), color spread (middle two panels), and subjective contour (right two panels) as a function of the logarithm of the luminance ratio of test dots and surround dots. Solid squares are data for red test and green surround (R/G), solid triangles for green test and red surround (G/R), and open squares for red test and red surround (R/R). The horizontal line marks the rating 2, "uncertain of the presence or absence of the attribute". Ratings above the line indicate presence of the attribute, below the line indicate absence. Errors bars are standard errors of the mean over observers for the color-normal observers and over sessions for the deuteranope.

the hue, saturation, or brightness of the subjective colors. Thus, in experiment 3, observers made color matches to the subjective colors seen in color from motion as the luminance ratio and chromaticity differences between test dots and surround dots were varied.

4.2 *Method*

4.2.1 *Stimuli.* Figure 2 (see page 1382) shows the observer's view in the color-matching experiments. The color-from-motion stimulus and the color-matching stimuli were presented on separate monitors. The color-from-motion stimulus was exactly the same as described in section 2.2. The observer's task was to choose which of two comparison stimuli better matched the subjective color seen in color from motion. The comparison stimuli were presented on a separate monitor (RasterOps 17 inch) as two circles (1.2 deg diameter, matching the test region of the color-from-motion stimulus) vertically separated by 0.4 deg within a 5 deg × 5 deg white square. The color-from-motion stimulus was separated by 12 deg from the comparison stimuli. The test/surround combinations were R4/G8, R8/G8, R8/G16, R8/G32, R16/G8, R16/G16, R16/G32, G4/R8, G8/R8, G8/R16, G16/R8, G16/R16, G32/R8, and G32/R16, where R denotes red, G denotes green, and the luminance is in units of cd m^{-2}. The luminance of the screen phosphors set a limit on the range of luminance values.

4.2.2 *Procedure.* The order of presentation of conditions was randomized over sessions. The stimuli were presented by using a staircase method, and the observer was asked to make a two-alternative forced choice on each trial. The two comparison stimuli presented on each trial differed slightly in either hue, saturation, or brightness. The observer's task was to choose which of the two better matched the spreading subjective color seen in the motion display. The results shown are the means over six sessions.

4.2.3 *Observers.* The observers were two of the six color-normal observers of experiment 1.

4.3 *Results and discussion*

The color matches to the subjective color spread are shown for two values of surround-dot luminance in figure 6 (surround-dot luminance 8 cd m^{-2}) and figure 7 (surround-dot luminance 16 cd m^{-2}). The luminance of the test was either 8 or 16 cd m^{-2}. Also shown in these figures are hue lines constrained to pass through the screen white and determined by the data. For surround-dot luminance of 8 cd m^{-2} and green test dots, color matches are clustered along the 554 nm hue line for observer EM and the 516 nm hue line for observer CC; for red test dots, matches are clustered along the 579 nm hue line for EM and 584 nm for CC. Increasing the luminance of the test dots increases

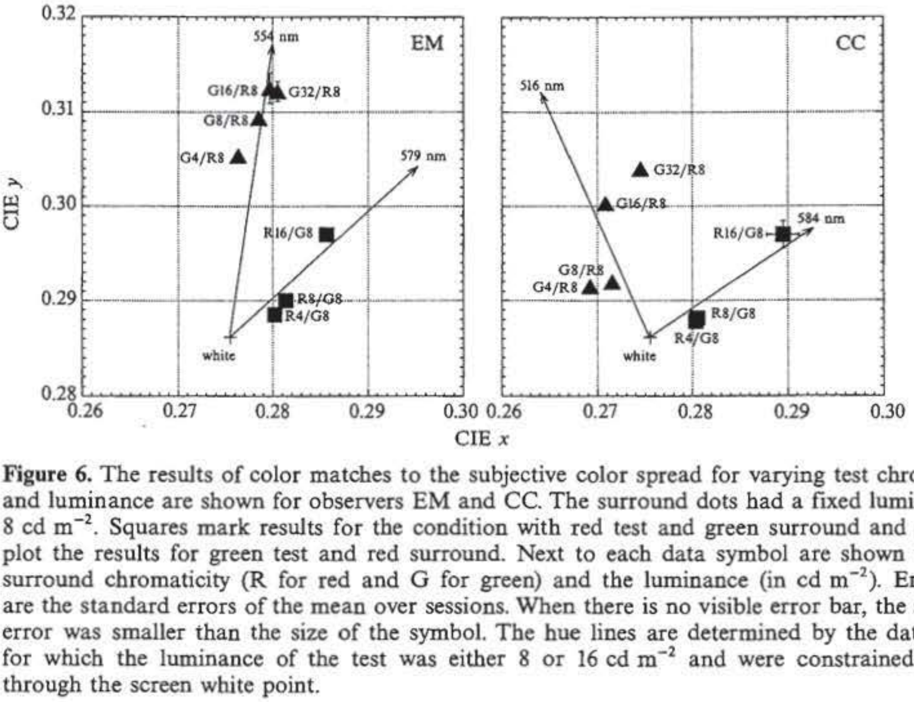

Figure 6. The results of color matches to the subjective color spread for varying test chromaticity and luminance are shown for observers EM and CC. The surround dots had a fixed luminance of 8 cd m^{-2}. Squares mark results for the condition with red test and green surround and triangles plot the results for green test and red surround. Next to each data symbol are shown the test/surround chromaticity (R for red and G for green) and the luminance (in cd m^{-2}). Error bars are the standard errors of the mean over sessions. When there is no visible error bar, the standard error was smaller than the size of the symbol. The hue lines are determined by the data points for which the luminance of the test was either 8 or 16 cd m^{-2} and were constrained to pass through the screen white point.

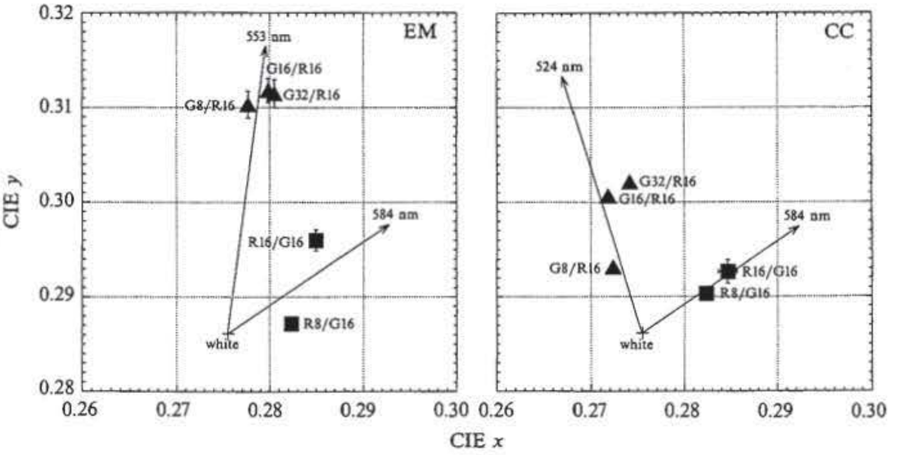

Figure 7. The results of color matches to the subjective color spread for varying test chromaticity and luminance are shown for observers EM and CC. The surround dots had a fixed luminance of 16 cd m^{-2}. Other details are the same as for figure 6.

the saturation of the subjective colors without changing the perceived hue. The same pattern of results is shown in figure 7 for a surround-dot luminance of 16 cd m^{-2}. The color matches for the conditions with green test dots are clustered along the 553 nm hue line for EM and 524 nm for CC; the results for the conditions with red test dots are clustered near the 584 nm hue line for both observers. These results show that increasing the luminance of the test dots increases perceived saturation with little change in the hue of the subjective colors.

Of equal interest is whether variations in the luminance of the surround dots produce changes in the color matches (figures 8 and 9). For observer EM, changes in surround luminance produce little change in either hue or saturation of the color matches. When test-dot luminance was held constant at 8 cd m^{-2}, this is shown by the clustering of her results for all values of surround luminance (figure 8, left panel). This same pattern was seen in observer EM's results with test-dot luminance held fixed at 16 cd m^{-2} and surround-dot luminance varied (figure 9, left panel). Observer EM's results are clustered near values determined by the chromaticity, red or green, of the

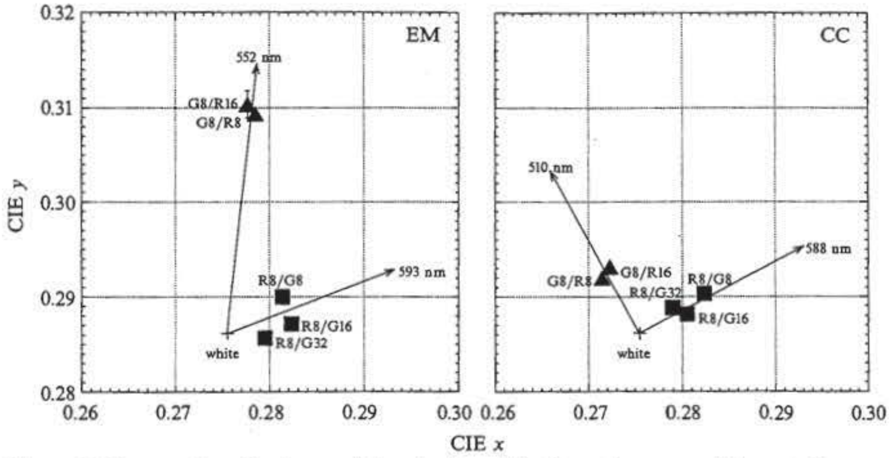

Figure 8. The results of color matches to the subjective color spread for varying surround chromaticity and luminance are shown for observers EM and CC. The test dots had a fixed luminance of 8 cd m^{-2}. The hue lines are determined by the data points for which the luminance of the surround was either 8 or 16 cd m^{-2} and were constrained to pass through the white point. Other details are the same as for figure 6.

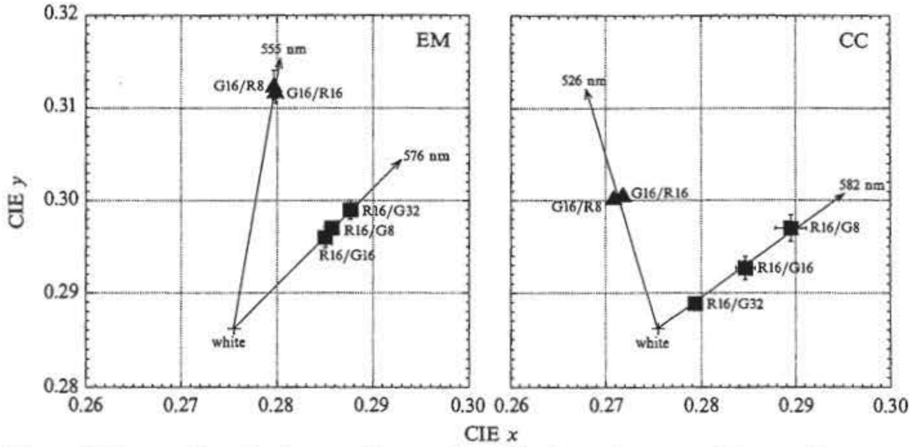

Figure 9. The results of color matches to the subjective color spread for varying surround chromaticity and luminance are shown for observers EM and CC. The test dots had a fixed luminance of 16 cd m^{-2}. Other details are the same as for figures 6 and 8.

test dots. The same is true for observer CC except for the condition with the red test dots of luminance equal to 16 cd m^{-2} and green surround dots of varying luminances (figure 9, right-hand panel). For this set, increasing the luminance of the surround dots produces a decrease in the saturation of the color matches to the subjective color without affecting the hue perceived.

For a fixed chromaticity of the test dots, the dominant wavelengths of the matches are stable over variations in test-dot and surround-dot luminances. For observer EM, the color matches in the conditions with green test dots shown in figures 6, 7, 8, and 9 yield values near 554, 553, 552, and 555 nm, respectively; for matches with red test dots, 579, 584, 593, and 576 nm, respectively. For observer CC, the color matches in the conditions with green test dots yield values near 516, 524, 510, and 526 nm, respectively; for matches with red test dots, 584, 584, 588, and 582 nm, respectively.

As expected, differences in the chromaticity of the test dots produced hue differences in the color matches to the subjective colors. If the chromaticity of the test dots was held constant while the luminance of the test dots was varied, color matches tended to lie farther from the white point, meaning greater saturation is perceived when test luminance is increased. The luminance of the surround had little impact on the color matches for the range of variations we used. Thus, in general, the hue of color spread depends on the chromaticity of the test dots and the saturation of color spread depends on the luminance of the test dots, and is independent of the luminance of the dots in the surround. In order to test these conclusions statistically, we performed a $2 \times 2 \times 2$ multivariate analysis of variance (MANOVA) on the data of each observer. The first factor was the chromaticity of the test (red or green), the second was the luminance of the test dots (8 or 16 cd m^{-2}), and the third was the luminance of the surround dots (8 or 16 cd m^{-2}). We could not match the other conditions shown in figures 6 through 9 because the full luminance of the red phosphor was less than half of that of the green phosphor. Table 2 shows a summary of the analyses for observers EM and CC. Only the results of main effects are shown. For both observers, the test chromaticity ($p < 0.001$ for both EM and CC) and the test luminance ($p < 0.001$ for both EM and CC) show high statistical significance, but the surround luminance ($p = 0.494$ for EM and $p = 0.898$ for CC) does not. The statistical analyses confirm that color from motion is determined by the chromaticity and the luminance of the test dots, but not by the luminance of the surround.

Table 2. Summary of multivariate analyses of variance for the color-matching data of experiment 3 (*** $p < 0.001$).

Observer	Source	df numerator	df denominator	*F*
EM	Test chromaticity	2	39	760.635***
	Test luminance	2	39	21.550***
	Surround luminance	2	39	0.71743
CC	Test chromaticity	2	39	512.685***
	Test luminance	2	39	56.180***
	Surround luminance	2	39	0.10833

5 Experiment 4: Surround chromaticity does not influence color from motion

5.1 *Introduction*

The results of experiment 3 show that, for the range of values we explored, the luminance of the surround dots has little or no impact on the hue or saturation of the subjective color seen in color from motion. Instead, the hue of the subjective color spread is determined by the chromaticity of the test dots, and its saturation is determined by the luminance of the test dots. Furthermore, the results of experiments 1, 2, and 3 show that a luminance difference between test and surround is not required for color from motion to be perceived as long as there is a chromaticity difference between dots in the test and surround regions. In experiment 4 we examined whether the chromaticity of the surround dots affects either the hue or the saturation of perceived color spread. This would be expected if color contrast plays a role in producing color spread from motion.

5.2 *Method*

The procedures and the observers were the same as in experiment 3. The stimuli differed in chromaticity; the luminance of the test dots was fixed at 16 cd m^{-2}, and the luminance of the surround dots was fixed at 8 cd m^{-2}. Test-dot chromaticity was red or green in combination with surround dots of the same or different chromaticity.

5.3 *Results and discussion*

Conditions in which test-dot chromaticity differed from surround-dot chromaticity were compared with conditions in which they were the same. For the conditions shown in figure 10, color matches depended on the chromaticity of the test dots, but were essentially unaffected by the chromaticity of the surround dots. The dominant wavelengths of the matches when test-dot chromaticity was green lie near the 555 nm hue line for EM and the 529 nm hue line for CC whether surround dots were red or green; and matches to the color spread for red test dots lie near 576 nm for EM and 581 nm for CC whether surround dots were red or green. Multivariate t^2-tests, involving the CIE x and y values, for differences between the means (table 3) show no significant differences between the pairs of matches except for a marginally significant difference between the conditions for green test dots and either a red or green surround for observer CC (F-value of 4.69 for this condition as compared with the 5% critical F-value of 4.26).

This result is somewhat surprising given the earlier finding that red surround dots can produce a subjective blue-green appearance in physically achromatic test dots (Cicerone et al 1995). One way to reconcile the two sets of experiments is to note the possibility that with a high-luminance white background and surrounds composed of

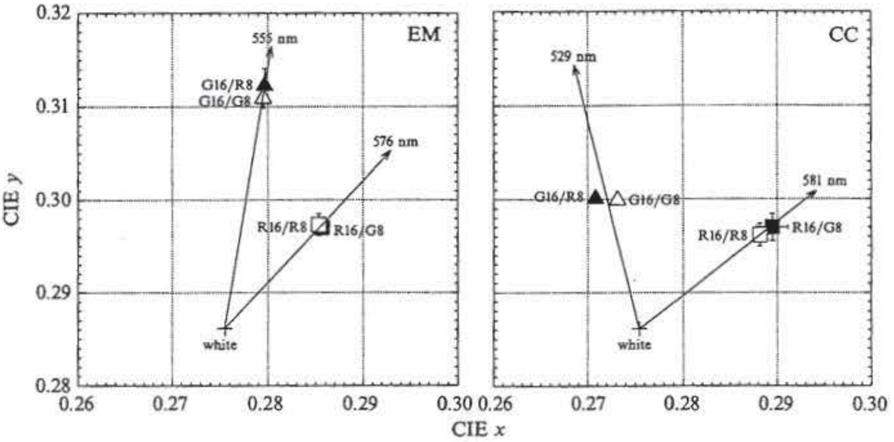

Figure 10. The results of color matches to the subjective color spread when the stimuli differed only in the surround chromaticities are shown for observers EM and CC. Test luminance was fixed at 16 cd m^{-2} and surround luminance was fixed at 8 cd m^{-2}. Closed symbols are conditions in which test-dot and surround-dot chromaticities were different (R/G or G/R). Open symbols are conditions in which test-dot and surround-dot chromaticities were the same (R/R or G/G). Error bars are the standard errors of the mean over sessions. When there is no visible error bar, the standard error was smaller than the size of the symbol. The hue lines are determined by the two data points and were constrained to pass through the white point.

Table 3. Summary of t^2-tests for the color-matching data of experiment 4 (* $p < 0.05$).

Observer	Condition	df numerator	df denominator	*F*
EM	R/G vs R/R	2	9	0.3040
	G/R vs G/G	2	9	0.2383
CC	R/G vs R/R	2	9	0.2238
	G/R vs G/G	2	9	4.6920*

colored dots, color-contrast effects can be induced on achromatic test dots but not on test dots of high chromaticity such as those used in these experiments. Although the range of luminances was limited by the characteristics of the phosphors, especially the red, the results of experiment 3 are consistent with the conclusion that the luminance of the surround dots have little or no effect on color from motion.

6 General discussion

We conclude that chromaticity differences alone between the test and surround dots can produce subjective color spread from motion. In this case subjective color spread is seen in the absence of a clear subjective contour (experiments 1 and 2). Luminance differences alone can also produce subjective color spread from motion (experiments 1, 2, and 3). Increasing the luminance of the test dots increases the saturation of the subjective color spreading in regions seen to be moving (experiment 3). Furthermore, for the conditions tested in experiments 3 and 4, the hue and saturation seen in color spread depend largely on the chromaticity and the luminance of the test dots, not of the surround dots. These results suggest that color from motion—the spread of subjective color in achromatic regions seen to be moving—may be regulated by mechanisms different from those regulating contour formation and color contrast.

In the well-known neon color effect (Varin 1971; van Tuijl 1975; van Tuijl and de Weert 1979; van Tuijl and Leeuwenberg 1979; Redies and Spillmann 1981; Ejima et al 1984; Redies et al 1984; Watanabe and Sato 1989), color is seen in static displays over regions which would be perceived as achromatic in isolation. A standard display is composed of radial lines of equal lengths; the inner segment of each line, for example half, is of one color (eg green) and the outer segment is of another color (eg black). In this case, one sees a green circular region defined by a subjective contour. The neon color effect has two distinct aspects: (i) achromatic regions near the green portions of the lines appear a desaturated neon green and (ii) a subjective contour is seen at the margin of the inner and outer segments.

Redies and Spillmann (1981) showed that the spread of neon color occurs in the static display even at equiluminance, as was confirmed experimentally by Ejima et al (1984). Grossberg and Mingolla (Grossberg and Mingolla 1985a, 1985b; Grossberg 1987) proposed a model in which two separate mechanisms are postulated, one to produce color spreading and the other to produce the subjective contour. In line with this model, the experiments of Watanabe and Sato (1989) showed that the neon color effect is seen without a subjective contour when the inner and outer segments are near equiluminance, suggesting that the perception of color spreading and the formation of a subjective contour are governed by two different mechanisms. In other experiments on luminance and contour formation such as Frisby and Clatworthy's (1975) study on the Kanizsa triangle (Kanizsa 1955), it was shown that a subjective contour is not seen when the stimulus is equiluminous. In this sense, neon color effects and color from motion share similar features. As equiluminance is approached observers report a reduction in the saturation of the subjective color spread and a greater reduction in the strength of the subjective contour.

As noted above, surround dots are required for this effect. Somewhat unexpectedly, the results of experiments 3 and 4 indicate that the hue and saturation seen in color spread from motion depend largely on the chromaticity and luminance of the colored test dots. In the ranges we explored, the chromaticity and luminance of the surround dots have little or no effect on color from motion. In a previous study (Cicerone et al 1995) achromatic test dots of varying luminance and red surround dots of fixed luminance were used. For some luminance values of the achromatic test dots, most observers reported a color change, from gray to blue-green, in the test dots but only when the stimulus was seen to be moving. Some observers saw the achromatic dots as blue-green in still view of a single frame and an enhancement when apparent motion was perceived. This is consistent with findings for the static neon color effect in which the chromaticity of the outer segments affects the chromaticity of color spread into achromatic regions near the inner segments (Ejima et al 1984; Bressan 1995). On the basis of these results, we expected to find that increasing the luminance of the surround dots or changing their chromaticity might enhance the subjective color spread seen in color from motion. Instead, for the range of luminance and chromaticity values we explored, our results show that the hue of the subjective color is determined by the chromaticity of the test dots and the saturation of the subjective color by the luminance of the test dots. Thus, in the present study, simultaneous color contrast appears not to play a significant role in producing the subjective colors seen in color from motion.

A number of observations of color phenomena—for example, Benham's top (1894) and Bidwell's ghost (1896)—associated with moving or rapidly changing colored or white stimuli have been reported since the nineteenth century (Cohen and Gordon 1949; Gregory 1987). Wallach's (1935) display is probably closest to our display. His stimulus consists of diagonal (up toward the left) stripes against a white background. Each diagonal stripe is painted black in the lower right part and red in the remainder (upper left part) with the margin between black and red defined by a vertical boundary. Although unreported by Wallach, in static view, color is seen to spread into achromatic regions near the red portions of each stripe and a clear subjective contour is visible at the boundary between red and black. In this respect, Wallach's display produces neon color spread similar to other static displays. When the bars are translated rigidly in a vertical, downward direction, the motion signal is inherently ambiguous, and observers report motion perceived in either downward or leftward directions. Wallach's (1935) observers reported seeing a subjective contour and the color-spreading effect if apparent motion was perceived horizontally, in a direction perpendicular to the color boundary, but not if apparent motion was perceived in a downward direction parallel to the subjective contour. (In our experiments with Wallach's stimulus, all observers saw color spread and a subjective contour in the static display; some, not all, observers saw an enhancement in the motion display.) In Wallach's report an enhancement of color spread was seen if the perception of apparent motion was in a direction aligned with the luminance and chromaticity change; and in this case Wallach's display produced results similar to those produced by our display. Wallach's display is different from ours in that a subjective contour and color spread were seen in the static view of his display (perhaps owing to assimilation) but not in ours.

Earlier studies were generally consistent with the view that the pathways for motion perception and for color perception are parallel and segregated (eg DeYoe and Van Essen 1985; Shipp and Zeki 1985; Movshon et al 1986; Shapley and Perry 1986; Hubel and Livingstone 1987; Lennie et al 1990). However, challenges to the notion of strict segregation of pathways for various perceptual properties such as motion and color have accumulated (eg Merigan and Maunsell 1993; Stoner and Albright 1993). There is now evidence that motion processing can rely on a segmentation of the visual image involving a variety of cues (eg Krauskopf and Farell 1990; Kersten et al 1992;

Kooi et al 1992; Trueswell and Hayhoe 1993), not luminance alone. Our studies (Cicerone et al 1995; Cicerone and Hoffman 1997; this study) suggest that the opposite may occur: motion perception may influence color perception. Two major pathways, the parvocellular and the magnocellular, carry information from the retina to higher centers. Studies on the functional capabilities of the macaque monkey after selective lesions of the parvocellular and magnocellular layers of the lateral geniculate nucleus suggest that, rather than being specialized for motion per se, the magnocellular pathway selectively processes stimuli of middle to high velocities whereas the parvocellular pathway selectively processes stimuli of low velocities (Merigan et al 1991; Merigan and Maunsell 1993). We have previously shown that in a display with both high-luminance and high-chromaticity contrast between the test (green, 68 cd m^{-2}) and surround (red, 20 cd m^{-2}) dots, apparent motion and subjective color spread are significantly reduced for velocities (as measured by rates of change in the dot color assignments) below 3 deg s^{-1} (Cicerone et al 1995). Accordingly, it cannot easily be argued that the parvocellular pathways itself is the substrate for the effects we call color from motion, thereby leaving open to question whether motion signals in the magnocellular pathway may affect color perception.

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