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Subjective Color from Apparent Motion

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In an effect we call *color from motion* (CFM), apparent motion is accompanied by subjective color spread seen in physically achromatic regions. Here we report that physical lights can cancel the subjective color seen in CFM. As measured by cancellation, the saturation of the subjective color spread increases as the luminance of the test elements increase. Without luminance differences between test and surround elements, chromaticity differences alone can result in the perception of subjective color spread. In this case, subjective color spread is seen without seeing a subjective contour, suggesting that CFM does not require contour formation and that color — independent of contour — can be recovered in tandem with seeing motion. There are two modes in which CFM is perceived, either (1) as a localized change of illumination, a colored spotlight or shadow, moving over a textured surface or (2) as a moving, colored object seen through holes in an occluding surface. The mode in which CFM is seen depends on figural cues and on regional differences in luminance contrast between the chromatic elements and the achromatic background. Regions with distinct figural cues are always seen as moving; and CFM is seen in the first mode if the regions are of lower luminance contrast and in the second mode if the regions are of higher luminance contrast. Without figural cues, the regions of lower luminance contrast are always seen to move and CFM is seen in the first mode.

Keywords: color, color from motion, apparent motion, motion, modal completion, amodal completion, illusory color, luminance contrast

Introduction

In static scenes, the human visual system can use fragments of information to perceive form by constructing subjective contours and color to fill in the missing parts of occluded objects through amodal completion (Michotte, Thines, & Crabbe, 1964; Kanizsa, 1979; Nakayama, Shimojo, & Ramachandran, 1990; Nakayama and Shimojo, 1990, 1992; Yamada, Fujita, & Masuda, 1993; Grossberg 1994). In the classic neon color spreading effect, the visual system uses another filling-in process: In static stimuli, illusory color enhances the perception of an object that is already suggested by fragments of its contour, shape, and color (Varin, 1971; van Tuijl, 1975). The perception of motion can also effectively break camouflage (Wertheimer, 1923). When something is partially occluded by other objects in the viewer's line of sight, relative motion can reconstruct the shape of the occluded object from successive partial views over time (kinetic occlusion), albeit with some distortion (Kaplan, 1969; Gibson, 1979; Andersen & Braunstein, 1983; Yonas, Crayton, & Thompson, 1987; Andersen & Cortese, 1989; Stappers, 1989; Shipley & Kellman, 1993, 1994). Recently, Cicerone, Hoffman, Gowdy, and Kim (1995) introduced an effect called color from motion (CFM) for which the perception of apparent motion is accompanied by a perception of subjective color, spreading into achromatic regions of the stimulus (see also Cicerone & Hoffman, 1992, 1997; Shipley & Kellman, 1994; Miyahara & Cicerone, 1997).

A typical CFM stimulus consists of multiple frames, each composed of an achromatic background over which lies a random array of small dots whose locations are fixed from frame to frame (Figure 1, left).
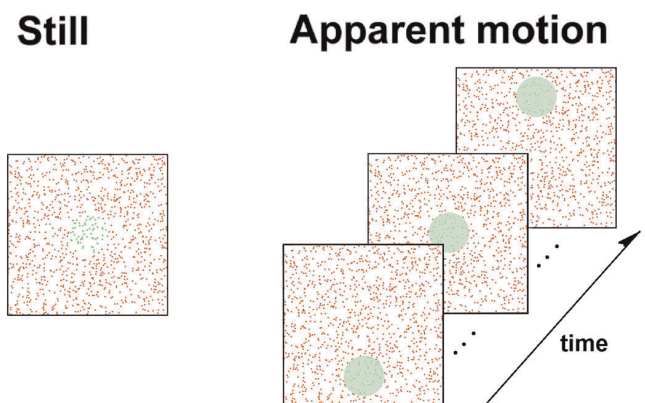

Figure 1. A still view of a single frame of the stimulus is shown on the left. As shown on the right, when frames are presented rapidly in succession, apparent motion is seen and subject color spreads into achromatic portions of the test region.

The dots within the test region (in this case, a disk) are assigned one color while the dots in the surround region are assigned a different color. The test region is then translated across the field of dots by changing only the color assignments of the dots from frame to frame while keeping dot locations unchanged in all frames. In this

example, the test dots are green, the surround dots red, and the achromatic background is of high luminance. In still view, a single frame is seen as a field of randomly scattered colored dots against a uniformly achromatic background (Figure 1, left). When frames are presented rapidly in succession, an illusory disk pops into view and appears to move with a velocity consistent with the translation of the test region. Linked to the perception of apparent motion, subjective color is seen to spread into the achromatic parts of the test region (Figure 1, right).

The effect can be seen in Movie 1 showing stimuli with green test dots of higher luminance than that of the red surround dots and a translation of the test region equivalent to a speed of 7 deg/s. Green subjective color can be seen spreading over the physically achromatic portions of the test region, and a clear subjective contour is seen. (Variations in luminance and chromaticity in different displays may give a less vivid effect in some demonstrations than were obtained in the experimental conditions.)
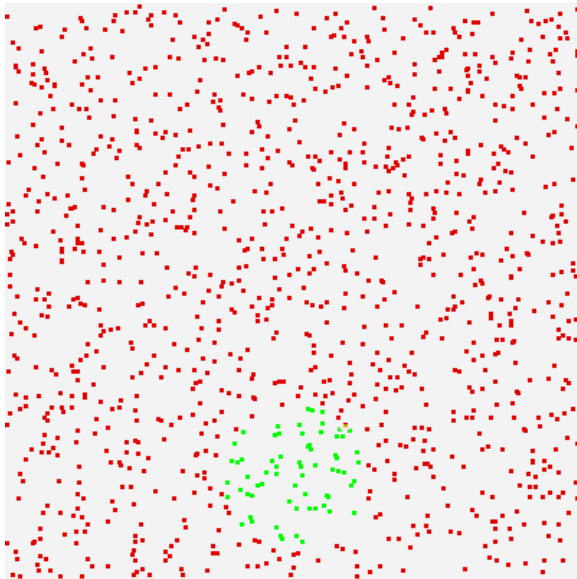
Movie 1. The color from motion effect is demonstrated with frames composed of an achromatic background of high luminance, green dots in the test region, and red dots in the surround. The green dots are of higher luminance than the red dots. Monitors and calibrations can vary. To enhance viewing this and other demonstrations, use a CRT display or a projector; avoid laptop LCD displays; reduce the ambient illumination; and avoid tracking the apparent motion.

The CFM effect is distinctive in a number of ways. First, neither contour formation nor neon color spreading is seen in still view of a single frame of the CFM stimulus. Second, in CFM displays, the only change from frame to frame is the color assignment of the dots; dot locations never change. Apparent motion and subjective color spread are generated strictly by the change in the chromaticity or luminance of the dots. In fact, if the test region remains fixed in space while the

dots in the test region are set in random motion, no color spread is observed. Third, subjective color spread yoked to motion is not reported in other effects involving the reconstruction of objects via motion; for example, it is not reported in structure from motion or in kinetic occlusion (Kaplan, 1969; Gibson, 1979; Andersen & Braunstein, 1983).

In this work, we report that a physical light can cancel the subjective color seen in CFM. As measured by cancellation, the saturation of the subjective color spread increases as the luminance of the test dots increase, whereas the luminance of the surround dots has relatively little effect. We also report that in the absence of luminance differences between test and surround elements, chromaticity differences alone can support the perception of subjective color spread, which, in this case, is seen in the absence of a subjective contour. This suggests that CFM does not require contour formation and that color — independent of shape — can be recovered in tandem with seeing motion. When clear figure versus ground cues are lacking, regions of lower luminance contrast (between the chromatic elements and the achromatic background) are the regions that are seen to move and over which subjective color spread occurs. Spatial configurations (figure/ground) can supersede luminance contrast relationships. Regions that appear as figure, even when they are of higher contrast, are seen as moving, in this case, as if behind a partially occluding surface.

Experiment 1

Physical Lights Can Cancel Subjective Color Spread in Color From Motion

Previous studies on CFM used rating methods to measure the perceived strength of the subjective color spread (Cicerone et al., 1995; Cicerone & Hoffman, 1997). Rating methods worked well in establishing the overall impression of the salience of the color spreading effect. However, certain aspects of the effect, such as the saturation of the subjective color, require a more quantitative methodology. Miyahara and Cicerone (1997) used a side-by-side matching method and found that the hue of the subjective color spread approximates that of the test dots. One drawback of the side-by-side matching method is that it requires the observer to compare the subjective color spread in CFM with a physical light that is situated in a different location and context. The impact of two possible contaminating factors was not controlled: (1) The matching stimulus was stationary whereas the CFM stimulus was perceived as moving, and (2) the matching stimulus was a homogeneously colored disk without test or surround dots as in the CFM stimulus.

One option would have been to pursue the color matching technique using a moving physical matching light situated in a field of dots.

Instead, in this work, we use a real light to cancel the subjective color spread in CFM. The test dots were produced solely with the green gun of the CRT display, the surround dots solely with the red gun, and the achromatic background by a combination of red, green, and blue guns in fixed proportion. Results of previous studies show that the desaturated subjective color spread over the test region has a chromaticity similar to that of the test dots (Miyahara & Cicerone, 1997). Therefore, the cancellation stimuli were produced by subtracting, from the background in the test region, small amounts of light of the same chromaticity as the test dots. Of course, removing green light results in a reduction in luminance of the background of the test region. Luminance was kept constant across the background of both test and surround regions by adding compensating amounts of red and blue lights – in the same fixed proportion as was used to produce the achromatic background – to the background of the test region. Hence, the cancellation stimulus is the amount of green light that has to be subtracted from the background of the test region, while holding luminance constant, for a perception of a uniform background across the stimulus. The observer's task on any trial is simply to judge whether or not the background in the test region appears to be reddish or greenish.
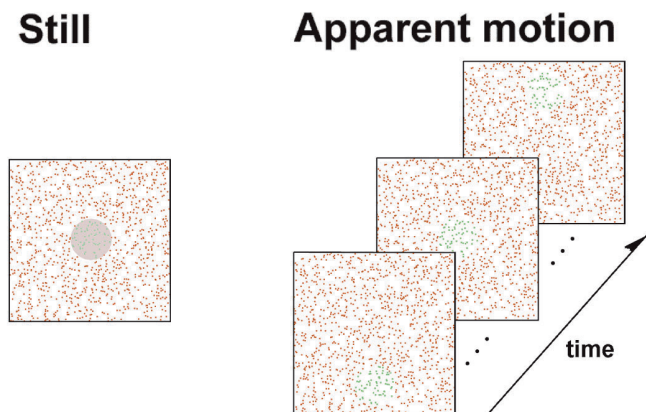

Figure 2. The cancellation stimulus, which appears reddish, is shown on the left in still view. As shown on the right, when frames are presented rapidly in succession, the subjective green color spread due to color from motion is cancelled and a homogeneous background is seen throughout the display.

The cancellation stimulus, which appears reddish, is depicted in Figure 2 (left). When the frames are cycled and apparent motion is seen, subjective green color spread is nulled by the cancellation stimulus and a homogeneous achromatic background is seen, as shown in Figure 2 (right).

Methods

Participants. Data were collected on two observers who were highly practiced and color normal (as assessed by color matches on the Neitz anomaloscope). Observers A and B were the authors.

Apparatus and stimuli. The stimulus was a square, each of whose sides subtended 8 degrees of visual angle viewed from a distance of 57 cm. The area of the CRT display outside the stimulus was set to the lowest luminance value and appeared black. The 2-degree test region contained dots colored green (CIE x = 0.280, y = 0.610) produced solely by the green gun of the CRT display; the surrounding region contained dots colored red (CIE x = 0.621 y = 0.344) produced solely by the red gun of the CRT display or green of the same chromaticity as the dots in the test region; the background of the surround region was achromatic (CIE x = 0.276 y = 0.286; 73 cd/m^2) produced by fixed proportions of the red, green, and blue guns of the CRT display. Individual dots were in fact squares, 3.5 minutes of arc on a side, composed of 9 adjacent pixels. The test region was translated up and down over a range of 5 degrees of visual angle at a displacement rate equivalent to 7 deg/sec. In the test region, varying amounts of green light were subtracted from the background of the test region (the cancellation stimuli), while keeping luminance constant and equal to that of the background in the surround region by adding compensating amounts of red and blue lights in the same fixed proportion as was used to produce the achromatic background. We plot, as cancellation value, the amount of green light (in luminance units) subtracted from the background region. There may be a number of alternative units, but all sensible units would be equivalent to our chosen unit, given that the chromaticity of the subjective color spread is equal to the chromaticity of the test dots. The stimuli were presented on a 21-inch Sony Trinitron CRT monitor driven by a Silicon Graphic Indigo II computer programmed using Open GL. The mapping between RGB values and output luminance of the three guns was measured (Photo Research model PR-650 Spectracolorimeter) and a gamma correction was applied to each gun to yield a linear function. The green test dot luminance was set at 18 or 36 cd/m^2. The red surround dot luminance was set at 4.5, 6, 9, 12, and 18 cd/m^2.

Procedures. Employing a two-alternative multiple-staircase forced response procedure, CFM displays with varying amounts of the cancellation stimulus were presented on each trial. Sitting in a darkened room, the observer was instructed to maintain fixation near the center of the display to judge whether the test region appeared to be greenish or reddish and to press response keys accordingly. The experiment was self-paced, with no fixed duration for each trial. The observer was free to view each stimulus for as long as necessary to make a decision. During each session, there were six conditions, with two separate staircases (one with an initial descent

and the other an ascent) per condition, randomly presented to the observer. Staircases terminated after three reversals. This procedure made it difficult, if not impossible, for the observer to track the progression of any particular staircase.

Results and Discussion

There was a systematic increase in the amount of the physical light required to cancel the subjective color spread as the luminance of the green test dots increased

from 18 to 36 cd/m^2. This result holds whether the outer dots are red (Figure 3) or green (Figure 4). Cancellation methods produce results that confirm those of earlier experiments (Miyahara & Cicerone, 1997) using side-by-side color matches showing that an increase in the luminance of the test dots produces an increase in the saturation of the physical lights required to match the subjective color spread.
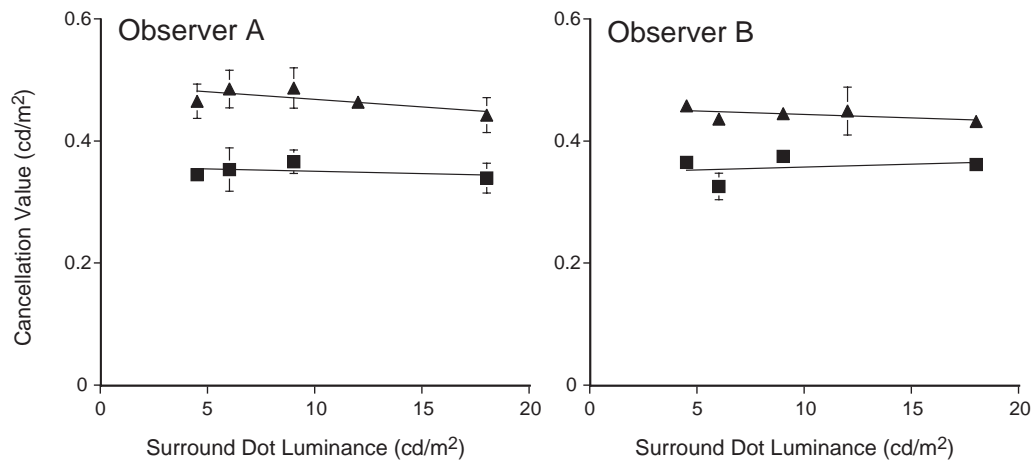

Figure 3. Plotted are the data (± 1 standard error of the mean) for Observers A (left) and B (right) with stimuli consisting of green test dots and red surround dots. Cancellation values increased as the luminance of the green test dots increased from 18 (squares) to 36 (triangles) cd/m^2. The surround dot luminance varied between 4.5 and 18 cd/m^2. The best-fitting straight lines to Observer A's data are shown (y = -0.0025x + 0.4938 at top and y = -0.0008x + 0.3589 at bottom). The best-fitting straight lines to Observer B's data are shown (y = -0.0011x + 0.4559 at top and y = 0.0009x + 0.3490 at bottom). The 95% confidence interval for the slope of each line includes zero. Surround dot luminance within the range tested does not affect the cancellation value.
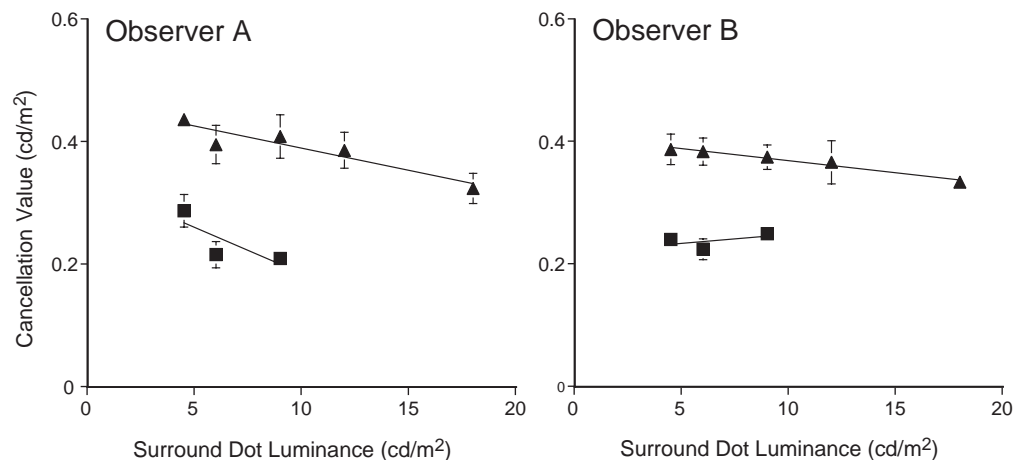

Figure 4. Plotted are the data (± 1 standard error of the mean) for Observers A (left) and B (right) with stimuli consisting of green test dots and green surround dots. Cancellation values increased as the luminance of the green test dots increased from 18 (squares) to 36 (triangles) cd/m^2. The surround dot luminance was varied between 4.5 and 18 cd/m^2. The best-fitting straight lines to Observer A's data are shown (y = -0.0072x + 0.4619 at top and y = -0.0151x + 0.3358 at bottom). The best-fitting straight lines to Observer B's data are shown (y = -0.0039x + 0.4083 at top and y = 0.0030x + 0.2192 at bottom). The 95% confidence interval for the slope of each line does not include zero, with the exception of the line through the data obtained with an 18 cd/m^2 test dot luminance for Observer B. Surround dot luminance within the range tested does affect the cancellation value. The cancellation value decreases as the difference in luminance of the test and surround dots decrease.

As Figure 3 shows, when the test and surround dots are of differing chromaticity, the surround dot luminance has little impact on the subjective color spread, as measured by cancellation, suggesting that the mechanisms underlying this effect are different from those for color contrast.

Whereas both color and luminance distinguish the test dots from the surround dots in the conditions represented in Figure 3, only luminance provides the difference between test and surround dots for the conditions of Figure 4 in which all dots share the same chromaticity. As test dot luminance increases, there is an increase in the cancellation value, as before. However, the results show that for fixed values of the test dot luminance, color spread as measured by cancellation is dependent on surround dot luminance: There is a decrease in the cancellation value as surround dot luminance increases. We note that without chromaticity differences, a luminance difference – between the test dots and the surround dots – is the only basis for the CFM effect. Hence, as test dot luminance and surround dot luminance become similar, the effect should dissipate, and it does.

Both chromatic differences and luminance differences play a role in CFM (Figures 3 and 4). The results of Figure 4 show that luminance differences alone are sufficient to produce CFM. Is a luminance difference required for the perception of color from motion?

One of the conditions shown in Figure 3 provides an answer. When the luminance levels of both the test and the surround dots are equal to 18 cd/m^2, the cancellation value is similar to that for all other conditions with the same test dot luminance, regardless of the luminance of the surround dots. Color spread is seen in the absence of a luminance difference between test and surround dots, as long as there is a chromaticity difference. Observers reported that in such equiluminant conditions, there is no clear contour bounding the region of the subjective color spread and that apparent motion is "not as smooth" and "slower" than the conditions in which the test and surround dots differ in luminance. These results are consistent with the established view that the neural processes responsible for illusory contours rely largely on luminance information (Kanizsa, 1979; Marr, 1982; von der Heydt, Peterhans, & Baumgartner, 1984). That subjective color spread is clearly seen for conditions in which test and surround dots are equiluminant indicates that the mechanisms underlying CFM are likely to be distinct from those that produce the perception of subjective contours. It should be noted that when a clear illusory contour is seen, the color spread is contained within the boundaries of the illusory contour, whereas when a clear contour is not seen, the subjective color appears to change its configuration over time. (One observer described the percept as "a moving, water-filled, colored balloon seen through a fog.") It is possible that the slow and unsteady motion and lack of a clear contour

perceived in the equiluminant condition are related to the properties of motion processing based on chromaticity differences alone (Cavanagh et al., 1984). It is noted that the color spread with equiluminant test and surround dots, as measured by cancellation and plotted in Figure 3, is just as salient as the conditions with surround dots of lower luminance. Movie 2 is a depiction of this effect.
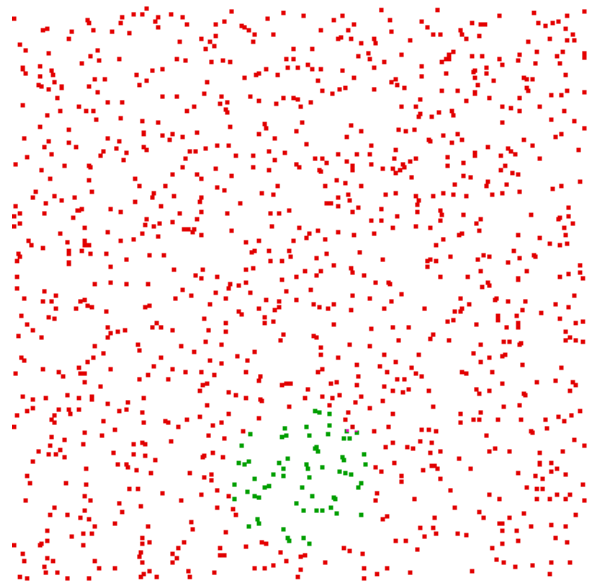
Movie 2. This demonstrates that color spread is seen in the absence of a luminance difference between test and surround dots, as long as there is a chromaticity difference. Observers reported that there is no clear contour bounding the region of the subjective color spread and that apparent motion is "not as smooth" and "slower" than the conditions in which the test and surround dots differ in luminance.

Experiment 2

The Perception of Motion Is Essential in Color From Motion

Subjective color spread in CFM is yoked to the perception of the motion of the test region (Cicerone et al., 1995). As such, it might be expected that the saturation, for example, of the illusory color in CFM, might depend on the salience of the apparent motion. In Experiment 2, we asked whether the subjective color seen in CFM, as measured by the cancellation method, changes as the translation speed of the test region is varied.

Methods

Participants. Observers A and B participated in this experiment.

Apparatus and stimuli. The basic stimulus design for this experiment was the same as in Experiment 1. The

green test dot luminance was fixed at 36 cd/m^2. The red surround dot luminance was set at 4.5, 9, or 18 cd/m^2. The translation speed, resulting from the rate of change of the color of the dots in the test region, was systematically varied from 0 to 12 degrees of visual angle per second. As in Experiment 1, the test region was translated up and down in a range spanning 5 degrees of visual angle.

Procedures. The procedures in this experiment were the same as in Experiment 1.

Results and Discussion

The results (Figure 5) for each observer can be described reasonably well by two linear functions with a markedly higher slope for the first linear branch compared to the second. The cancellation value for the subjective color spread increases rapidly in the first branch as speed increases to about 1 deg/s.
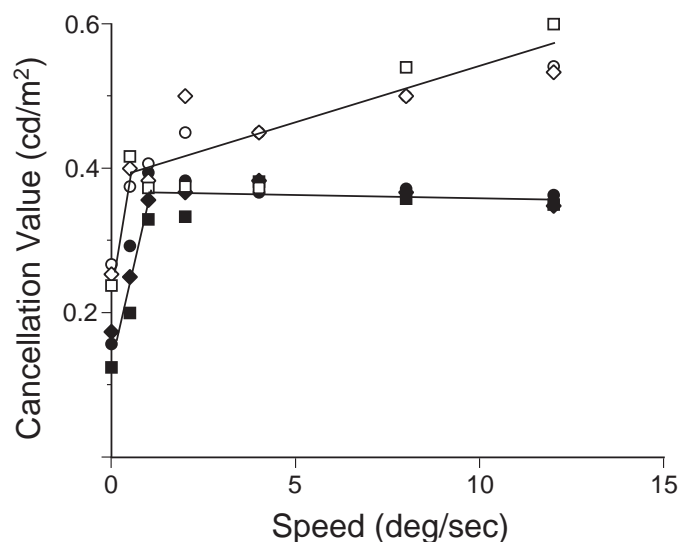

Figure 5. Cancellation values as a function of speed varying between 0 and 12 degrees of visual angle per second are shown for Observer A (closed symbols) and Observer B (open symbols). The luminance of the test dots was fixed at 36 cd/m^2 and that of the red surround dots was 4.5 (circles), 9 (diamonds), or 18 (squares) cd/m^2. The best-fitting straight lines to Observer A's data are y = 0.0209x + 0.0149 for x ≤ 1 and y = -0.0001x + 0.0367 for x ≥ 1. The 95% confidence interval for the slope β of the second line describing Observer A's results is -0.0005 ≤ β ≤ 0.0003. The best-fitting straight lines to Observer B's data are y = 0.0135x + 0.0278 for x ≤ 1 and y = -0.0015x + 0.0386 for x ≥ 1. The 95% confidence interval for the slope β of the second line describing Observer B's results is 0.0012 ≤ β ≤ 0.0018.

For Observer A, the data for speeds greater than 1 deg/s are well fit by a line of slope near zero (95% confidence interval for slope β, -0.0005 ≤ β ≤ 0.0003). For Observer B, although the rate of increase in the second branch is not zero, the results indicate a highly reduced rate (slope decreases 15-fold) of change in color

spread as speeds increase beyond 1 deg/s. This profile of the results suggests an all-or-none relationship between apparent motion and subjective color spread.

Although there appears to be no color spread in still view of single frames of the CFM stimulus, we decided to perform the cancellation experiment with a single still frame. There is a small but significant color spread as measured by the cancellation method (results plotted for 0 deg/s in Figure 5). This indicates that the cancellation method is highly sensitive. One possibility is that the color spread in still view can be attributed to the well-known assimilation effect – von Bezold's (1874) spreading effect. It is beyond the scope of this study to determine the exact source of the measured color spread in static view. For our purposes, it suffices to note that each of the measurements of color from motion in Figure 5 includes a constant value of color spread inherent in still view of a single frame, whatever the source, and, more important, that the results cannot be accounted for by color spread attributable to static effects alone.

As the translation speed of the test region increases, the perception of the illusory disk as separate from the field of dots becomes more salient. The perception of separation is nearly absent until translation speeds of 1 degree of visual angle per second are exceeded. For speeds greater than 1 degree of visual angle per second, there is an increased tendency for observers to report seeing the subjective color spread and its associated illusory disk as a patch of light totally separated from and lying over the field of dots. At the same time, the test dots appear to assume the color of the surround dots, resulting in the perception that all of the dots are of the same color, in this case red. Thus, it appears that translation speeds greater than 1 degree of visual angle per second produce little or no enhancement of the subjective color spread but can influence the salience of separation between the figure defined by the subjective color spread and the array of dots.

Experiment 3

Modal Versus Amodal Completion in Color From Motion

The subjective color spread in CFM for the stimuli of Experiments 1 and 2 has a neon or glowing quality with the illusory figure, defined by the color spread, moving over the array of dots. We call this percept *modal completion* and classify it with other effects such as transparency and the neon star (Michotte et al., 1964; Varin, 1971), for which there is color spreading into physically achromatic regions interpreted as a spotlight, transparent layer, or shadow. In natural scenes, objects that are screened from full view are perceived as moving behind screening elements. A previous study (Cicerone &

Hoffman, 1997) described CFM aligned with this natural situation. In this case, a perceptually complete, moving object is seen through holes in an occluding surface. The perceived color of the object exactly matches that of the dots. We call this percept *amodal completion* to signify that the observer perceives the presence, the shape, and the color of an object behind the occluding surface. In Experiment 3, we systematically varied the background luminance while holding test dot luminance constant. In the static display, lowering the luminance of the background progressively produces the impression that the dots are sources of illumination – aperture colors rather than focal colors. Therefore, we hypothesized that there should be an abrupt switch, from modal to amodal completion, near the point of equiluminance between test dots and the background region. This effect is demonstrated in Movie 3.
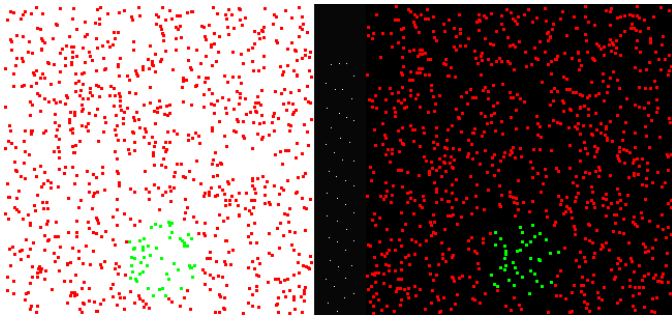
Movie 3. The red and green dot luminance levels for the display on the left match those for the display on the right. The only difference between left and right displays is the luminance level of the background. When frames are animated, modal completion is seen on the left and amodal completion is seen on the right.

Methods

Participants. The same two observers of Experiments 1 and 2 participated in this experiment.

Apparatus and stimuli. The CFM stimulus for this experiment was the same as that in Experiment 1 with the following exceptions. Three combinations of test (green) and surround (red) dot luminances were used: 18 cd/m^2 and 18 cd/m^2, respectively; 9 cd/m^2 and 18 cd/m^2, respectively; 18 cd/m^2 and 9 cd/m^2, respectively. The luminance of the achromatic background region ranged from 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, to 33 cd/m^2.

Procedures. The observers were first asked to view a range of stimuli, while maintaining fixation near the center of the display, and were asked to describe what they saw. The observers spontaneously described the percept in one of two ways: In the first, a green color spread of low saturation that is likened to a green spot light is seen moving over a field of red dots. This was classified as modal completion. In the second, a colored, moving shape is seen as if through holes in a dark surface.

The object appears to lie behind the dark surface and its color appears to match the color of the green test dots. This was classified as amodal completion. As the luminance of the achromatic region was randomly varied between 0 and 54 cd/m^2, the observers were asked to identify which of the two possible percepts was seen. Equiluminance for each observer was based on flicker photometric matches for the red, the green, and the achromatic stimuli using circular fields of diameter 2 degrees of visual angle, matching the size of the test region.

Results and Discussion

The results show an abrupt switch from modal to amodal color spread that occurs near the point of equiluminance between the test dots and the achromatic region (Figure 6).
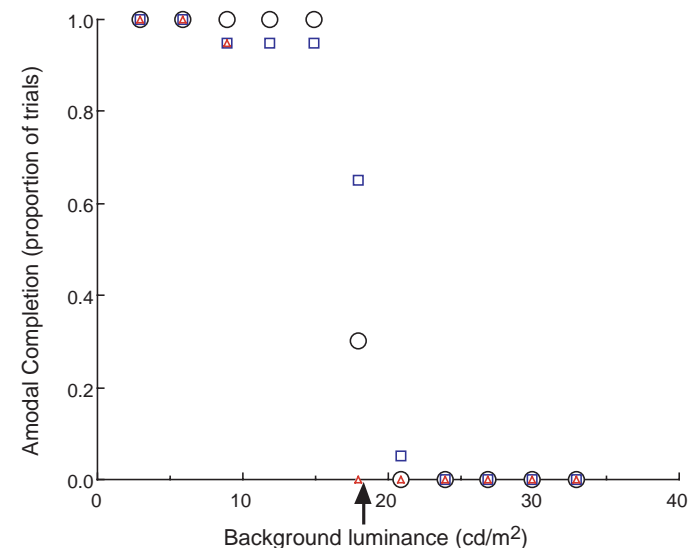

Figure 6. Results for Observer A are shown. The proportion of trials on which amodal completion is seen was plotted as a function of background luminance, varying between 3 and 33 cd/m^2. The results were similar for conditions in which green dot luminance equaled red dot luminance set at 18 cd/m^2 (circles); green dot luminance set at 9 cd/m^2 and red dot luminance at 18 cd/m^2 (squares); and green dot luminance set at 18 cd/m^2 and red dot luminance at 9 cd/m^2 (triangles).

Observers reported that when modal completion is perceived, the colored dots appear to be textures lying on a bright surface. The color spread in modal completion appears to be interpreted as a spotlight that produces a change in the luminance and color over the test region, which otherwise is identical to those in the surround. When amodal completion was perceived, the colored dots appear to be holes in a dark screen, lying in the foreground, through which a bright, uniformly colored, moving object is seen. In either case, the color spread was seen to belong to an object separate from the field of dots.

The appearance of the subjective color spread can be strikingly different, depending on the luminance of the background field. Changes in the luminance of the background appear to determine whether the dots are perceived as texture on a reflective surface or as apertures in an occluding screen. In the former case, modal completion occurs and observers judge that color spread lies on top of the field of dots; in the latter case, amodal completion occurs and observers judge that an object is moving behind the surface of the dots. In either case, there appears to be a clear separation of the color spread and the surface containing the dots. These conclusions apply to the special case of a stimulus with clear figure/ground cues; therefore, the next experiment was designed to consider the impact of luminance relationships for stimuli without figure/ground cues.

Experiment 4

Luminance Relationships Determine the Organization of the Moving Scene

In still view of the stimuli in Experiments 1, 2, and 3, the small circular test region is clearly seen as the figure and the region of red dots as ground. In this case, the test region is always seen to move and color spread is linked to this moving region. Suppose figure/ground configuration is not as evident. Do the luminance relationships among green dots, red dots, and the background become more important in determining the area that is seen to move and over which subjective color spread is seen? To answer this question, the first set of stimuli for Experiment 4 were composed of bands of equal width, alternately filled with green and red dots. Luminance contrast between the red dots and the background compared to that between the green dots and the background was varied. Based on the results of Experiment 3, we predicted that apparent motion would be seen more readily in the regions of lower contrast (Figure 7).

If apparent motion triggers color spread, as we have argued based on the results of Experiment 2, then color spread should also occur over the regions of lower contrast. In the second part of Experiment 4, we reduced the width of the band of green dots to make this region appear more figure like.

Methods

Participants. Observers A and B of Experiments 1 and 2 participated in this experiment.

Apparatus and stimuli. In the first set, the stimulus frame was divided into four vertical strips of equal width. The dots within each strip were all assigned one color, alternating red and green. Multiple frames were created by a uniform horizontal translation of the color assignment. Frames were cycled at a rate equivalent to 7

deg/s. The luminance of the achromatic region was set at zero for the low background luminance condition and at 81 cd/m^2 for the high background luminance condition. The luminance of the red dots in the surround was held constant at 18 cd/m^2. The green test dot luminance ranged from 4.5, 9, 13.5, 18, 27, 36, to 54 cd/m^2. In the second set, the width of the strip in which dots were colored green was decreased from one-fourth, one-eighth, to one-sixteenth of the screen width.

Procedures. Equiluminance between the red and the green stimuli was measured by the method of minimally distinct borders (Boynton, Hayhoe, & MacLeod, 1974). For every experimental condition, observers were instructed to report whether they saw the red bands or the green bands moving.
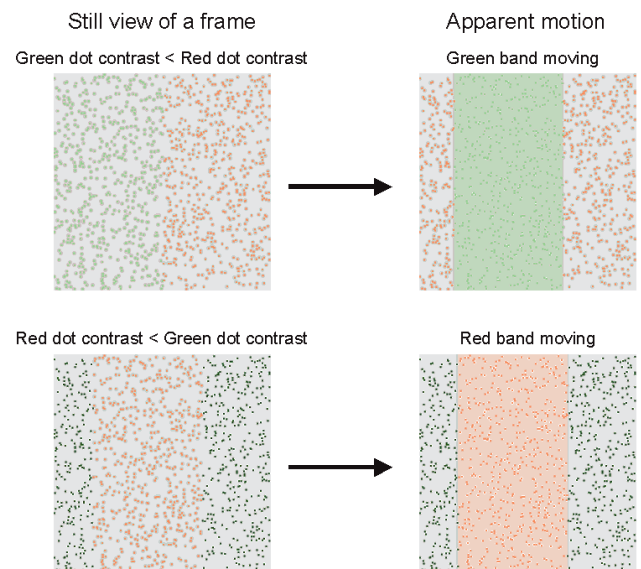

Figure 7. The green dot luminance is higher for the stimulus at the top compared to that at the bottom; in all other respects, the stimuli are identical. For the top stimulus, green dot contrast against the background is less than red dot contrast against the background. When frames are animated, we predict that observers will see a uniformly colored green band moving over a field of stationary red dots. When red dot contrast is less than green dot contrast (bottom), we predict that a uniformly colored red band will be seen moving over a stationary field of green dots.

Results and Discussion

The results of Experiment 4 are shown in Figure 8 for low and high luminances of the background. Regardless of background luminance, apparent motion and color spread are associated with regions of lower luminance contrast. The switch in perception between seeing red bands moving or green bands moving occurs abruptly at each observer's point of equiluminance between red and green.
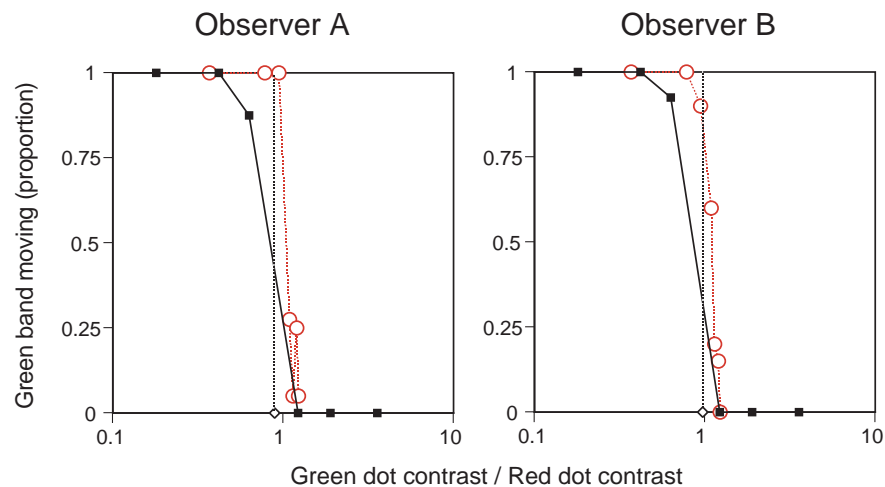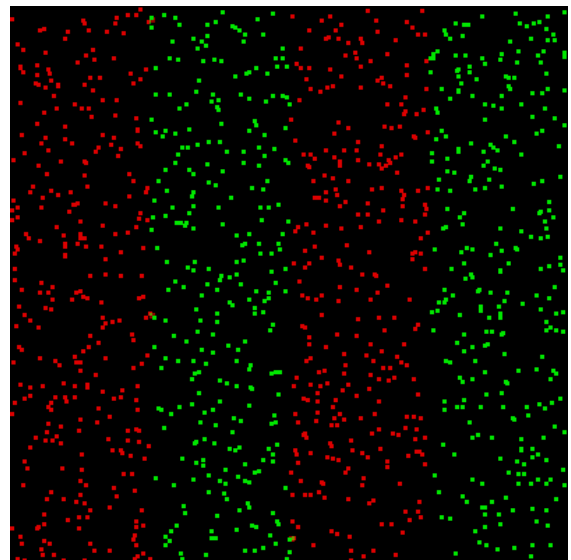
Figure 8. The horizontal axis plots the ratio of the green dot contrast against the background compared to red dot contrast against the background. The vertical axis plots the proportion of trials on which a green band is seen to move over a field of red dots. Closed squares plot the results for a low luminance background. Open circles plot the results for a high luminance background. The diamond plots the equiluminance point between red and green as measured by the method of minimally distinct borders.

When clear figure/ground cues are lacking, luminance contrast between the chromatic elements and the achromatic background determines which regions are seen as moving and filled with subjective color. When green dot contrast against the background is less than red dot contrast against the background, observers see a uniformly colored green band moving over a field of stationary red dots in the CFM stimulus, and vice versa. Movie 4 demonstrates this effect for the condition in which the contrast between luminance of the green dots compared to the luminance of the background is less than that between the red dots and the background.
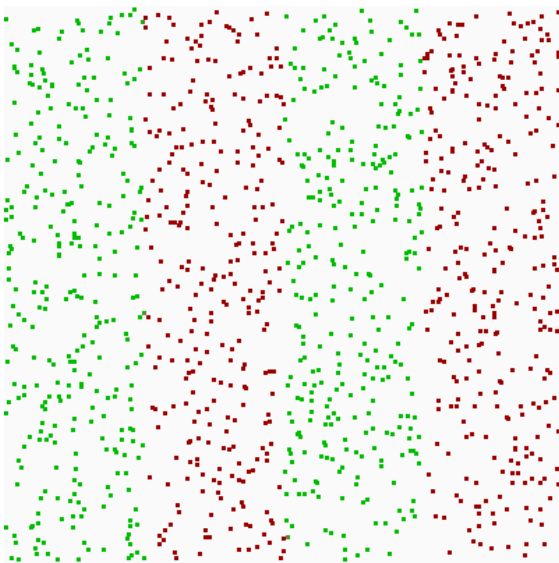
Movie 4. Here the contrast between the luminance of the green dots and luminance of the background is less than that between the red dots and the background. A uniformly colored green band is seen moving over a stationary field of red dots.

As shown in the results of Figure 8 and depicted in Movie 5, the same contrast rule holds for backgrounds of low luminance. It is always the case that apparent motion and subjective color spread are associated with regions of lower contrast.

Movie 5. This movie is identical to the previous one, except for a lower background luminance. Now the red dot contrast is less than green dot contrast against the background. Observers see uniformly colored red bands moving over a field of green dots.

As figure/ground cues are enhanced, will regions of lower contrast still be seen to move? The width of the band of green dots was successively narrowed with the idea that a narrow enough band should appear like a figure against a larger background of red dots. The results are shown in Figure 9.
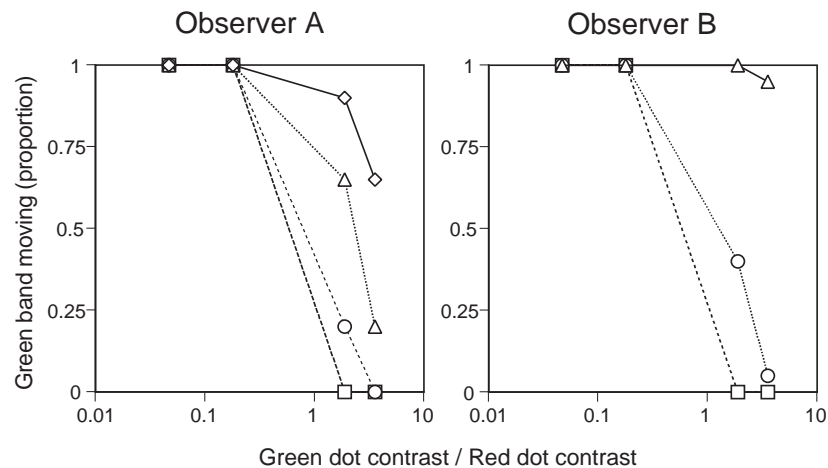
Figure 9. The horizontal axis plots the ratio of the green dot contrast compared to red dot contrast against the background. The vertical axis plots the proportion of trials on which the green band is seen to move over a field of red dots. The band of green dots spanned one-half (squares), one-fourth (circles), one-eighth (triangles), or one-sixteenth (diamonds) of the width of the screen. The results for a high luminance background are plotted. Results are similar for a low luminance background.

As shown in these data, configurations of the test and surround elements that support figure/ground interpretations can supersede luminance contrast relationships so that regions that appear as figure rather than ground are seen as moving. When the width of the band of green dots is large, either one-half or one-fourth of the width of the screen, the region containing the dots with lower contrast relative to the background is seen to move, whether the dots are colored red or green. When the width of the band of green dots is reduced to one-eighth (Observer B) or one-sixteenth (Observer A), the likelihood of seeing the green band moving is enhanced, even if the red dots have lower contrast relative to the background.
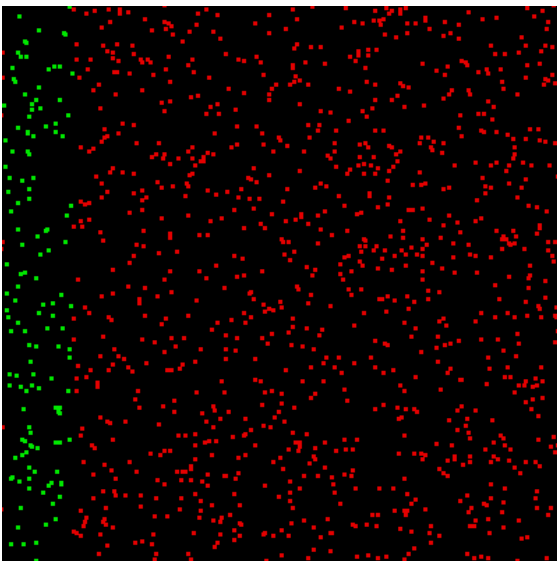
Movie 6. This movie uses a thin figure-like region of green dots and the same luminance contrast relationships as Movie 5. Given the luminance contrast relationships, the red band is always seen as moving in Movie 5. The figural cue enhances the likelihood of seeing a moving green band in Movie 6.

Movie 6 illustrates that figure/ground configuration can supersede luminance relationships. A figure-like region (in this example, a thin strip of green dots) is seen to move even if in that region the luminance of the dots against the luminance of the background is of higher contrast compared to the luminance contrast of the region of red dots.

General Discussion

In this study, a quantitative measure of the subjective color spread in CFM was established using cancellation with physical lights. This measure served as the basis for assessing the roles of chromaticity and luminance on the subjective color perceived in color from motion. The saturation of the subjective color spread appears to depend on the luminance of the test dots but not on the luminance of the surround dots. This experimental observation suggests that mechanisms regulating color from motion are not the same as those for conventional color contrast, which is strongly dependent on surround luminance. With a luminance difference between the dots in the test and those in the surround region, observers perceive an illusory contour that borders the color spread. Without a luminance difference between test and surround dots, chromaticity differences alone are sufficient to produce subjective color spread in CFM. In this case, color spread occurs without an illusory contour. This suggests that the neural substrate for the subjective color spread is likely to be distinct from that generating illusory contours. Furthermore, subjective color spread without a subjective contour is consistent with the view that higher-level interactions may influence the perception of seemingly primitive features like brightness and color (e.g., Nakayama et al., 1990; Merigan & Maunsell, 1993; Cicerone et al., 1995).

Although perceived motion of the test region in the CFM display is critical for subjective color to be seen, translation speeds greater than 1 deg/s do little to enhance the salience of the subjective color spread as measured by cancellation. Thus, motion appears to act like a gating mechanism for the perceived color spread. The perception of motion and subjective color spread in CFM is also accompanied by a perceptual rearrangement of the visual scene such that an object appears to be moving in front of or behind the field of dots. It is possible that these perceptions, gleaned from fragmented physical information, may be due to representations of visual objects and the scene as a whole at relatively high levels of visual processing, as noted above.

The Distinctive Features of Color From Motion

The CFM effect is distinctive in a number of ways. First, neither contour formation nor neon color spreading is seen in still view of a single frame of the CFM stimulus. In this way, it is clearly different from static neon color spreading, an effect that is already well established. Furthermore, subjective color spread as seen in CFM is not present in all motion stimuli; for example, it is not reported in kinetic occlusion. Second, in CFM displays there is no spatial dislocation of the dots; the only change from frame to frame is the color assignment of the dots. Apparent motion — accompanied by subjective color spread — is generated strictly by the change in chromaticity or luminance of the dots. To reinforce this point, we asked naïve observers to view the following stimuli in which the test region remains fixed in space and the test dots themselves are set in motion either (1) independently and randomly; (2) in unison along a linear trajectory; or (3) in unison along a random trajectory. In all of these cases, none of the observers reported seeing color spread associated with the physical motion of the test dots. Third, as shown in Experiment 1, the luminance of the dots in the region surrounding the test have no influence on the subjective color spread when test and surround dots are of different chromaticity This is consistent with the view that color from motion is distinct from color contrast. Fourth, subjective color spread is seen without the perception of a subjective contour when test and surround dot luminance levels are comparable, as long as there is a chromaticity difference. This result presents difficulties for explanations of CFM requiring the prior formation of contours before the filling-in of illusory color. Furthermore, this result supports the view that color — independent of contour — can be recovered in tandem with seeing motion.

Metelli (1974) developed luminance criteria that are critical for the perception of transparency of achromatic surfaces. The model specifies that transparency is perceived in bounded regions of reduced contrast. This principle serves well to identify the presence of transparent filters or shadows in the natural environment, because both filters and shadows produce regional reductions in luminance contrast. The conditions under which transparency is perceived have been posed as requirements based on luminance or lightness (Metelli, 1974; Beck, 1978; Beck, Prazdny, & Ivry, 1984; Gerbino, Stultiens, Troost, & de Weert, 1990; Fukuda & Masin 1994); on spatial configuration (Tudor-Hart, 1928; Heider, 1932; Watanabe & Cavanagh, 1993; Adelson, 1993); on motion (Adelson & Movshon, 1982; Kersten, Bülthoff, Schwartz, & Kurtz, 1992; Mulligan, 1993); on stereo disparities of stimulus components (Nakayama et al., 1990); and on chromatic properties (da Pos, 1989; Faul, 1996; D'Zmura, Colantoni, Knoblauch, & Laget; 1997; Chen & D'Zmura, 1998).

Is color from motion the same as transparency? When color from motion is seen in modal completion, the low saturation and neon-like quality of the subjective color spread is reminiscent of the quality of the perception in transparency. Nonetheless, we argue that the subjective color seen in CFM and that seen in transparency are distinct for the following reasons. First, as noted above, the perception of transparency occurs in classical displays due to both figural and luminance cues already present in the stimulus. On the other hand, in CFM, a layer of illusory color is perceived to spread into physically achromatic regions of the stimulus to create a new colored surface, with or without a border. In other words, when transparency is perceived, physically differentiated surfaces are conjoined to create a unified perceptual layer, whereas in CFM, an entirely new surface is created by illusory color spread. Second, motion is not required for transparency to be perceived, whereas subjective color spread in CFM is seen only in tandem with apparent motion and is never seen in still view of single frames. Third, for conditions in which modal completion of a neon-like color spread is not perceived, CFM is still achieved, in this case by amodal completion in which the moving, colored object is perceived to lie behind — rather than in front of — a partially occluding surface. Examples are presented in Movie 3, right, and in Movie 6.

The Neural Basis for the Perception of Color From Motion

A number of studies have suggested that the visual pathway is separated into independent channels of feature processing (as reviewed in, e.g., Lennie, 1980; Merigan & Maunsell, 1993). In particular, anatomical or physiological linkages that serve as a possible substrate for cross talk between motion processing and color processing have not been identified. The perception of color from motion raises the possibility of such interactions. Is there evidence supporting the idea that such interactions may occur at an early stage of visual processing?

Stimuli that produce the perception of modal completion of illusory contours in humans produce activity consistent with such a perception in neurons of primate V1 (Grosof, Shapley, & Hawken, 1993) and V2 (von der Heydt et al., 1984; von der Heydt & Peterhans, 1989; Peterhans & von der Heydt, 1991). Sugita (1999) provides evidence supporting the possibility that amodal completion may occur early in visual processing, namely primate V1. When two line segments are separated, they are grouped together and perceived as a single vertical bar if the region separating them has a crossed disparity but not if the region has an uncrossed disparity. This is consistent with the visual system's interpretation of the region lying in front (crossed disparity) or behind (uncrossed disparity) the line segments. Sugita recorded the response properties of orientation-selective cells, including both simple and complex cells, in V1 of Japanese monkeys presented with such stimuli. Simple cells and complex cells showed comparable responses to physically continuous line segments and to stimuli requiring amodal completion. Because the latency of the response for the completion of the line segments behind the patch was not different from that for a physically defined line, Sugita argued that it was unlikely that completion relied on feedback signals from extra striate areas (Zipser, Lamme, & Schiller, 1996). Instead, Sugita argued that the likely mechanisms underlying amodal completion are supplied by the lateral connections in V1. Although it has often been suggested that the amodal completion of illusory contours might be based on higher level processing, perhaps a kind of cognitive reasoning, Sugita's work offers support for the possibility that neuronal mechanisms at very early stages of the visual system may be able to perform rather sophisticated processing. There is no assurance, of course, that human visual processing should be identical to that of other primates. Evidence using fMRI methods suggest that in humans extrastriate areas are mainly involved in processing illusory contours (Hirsch et al., 1995; Mendola, Dale, Fischl, Liu, & Tootell, 1999). More recently, fMRI measurements made with moving illusory contours (Seghier, Dojat, Delon-Martin, Rubin, Warnking, Segebarth, & Bullier, 2000) suggest that V5 and V1 are also activated.

If we assume that, as Sugita (1999) suggests, the lateral connections of V1 neurons are capable of sophisticated tasks like modal and amodal types of illusory contour completion, is it likely that color from motion also can be explained by V1 mechanisms? Some of our own results are compatible with this scheme. For example, results based on ratings show that the sequential frames of the CFM display can be presented alternately to one eye and then the other — odd numbered frames to one eye and even numbered frames to the other — to produce an effect that is equal to full presentation to one or both eyes (Cicerone & Hoffman, 1997; Experiment 1). However, there are a number of reasons why we think

that explanations based on V1 mechanisms alone may not be sufficient to explain color from motion. One difficulty of extending findings based on static displays to color from motion stimuli is that color from motion requires the perception of apparent motion. To our knowledge, based on evidence from primate recordings, only cells in MT respond to apparent motion stimuli as they would to real motion stimuli (Newsome, Mikami, & Wurtz, 1986; Kaneoke, Bundou, Koyama, Suzuki, & Kakigi, 1997). Unlike the static illusory contour or neon color spreading stimuli used in previous studies, color from motion does not occur at all in static stimuli. Furthermore, the second set of results in Experiment 4 show that figure/ground configuration can override luminance relationships as the determinant of which areas appear to move and to be filled with subjective color. As it is currently understood, figure/ground organization is likely to depend on higher level visual processing.

The Functional Significance of Color From Motion

In natural scenes, objects or surfaces may not be seen in the jumble of color, luminance, or texture of nearby surfaces. In other cases, objects may be hidden from full view by occluding surfaces. Although restricted parts of the object can be seen through gaps in the screening elements, often neither the object, nor its color, nor its location is perceived. In still view, the physical representation in such scenes gives only an equivocal or fragmented definition of the object and its surround. When the hidden object moves relative to the rest of the scene, subjective color spread helps to reveal the object as if in plain view. The results of this study show that color from motion can be seen in two modes. In modal completion, the subjective color spread is of low saturation and has a neon-like quality. This mode evokes the perception of a colored light or shadow moving over the scene. In amodal completion, an object filled with color is perceived to be moving behind a punctuated surface. We propose that color from motion works in natural scenes as an organizing mechanism that reveals localized regions of illumination or partially occluded objects.

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