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Rapid communication

Depth from subjective color and apparent motion

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Abstract

We report that color and depth, as well as form, are recovered in tandem with seeing motion. The stimulus, consisting of multiple frames, was designed to keep all aspects, except color, of the binocular images identical. In still view, rivalry occurs due to the unmatched color of some corresponding image elements in the two eyes. When frames—created by translating color assignments and nothing else—are rapidly cycled, a *colored* object is seen *moving in depth*. In natural scenes the same mechanisms may be used to reconstruct depth, color, and form of hidden objects so that they can be seen as if in plain view.

Keywords: Color; Depth; Motion; Binocular vision; Occlusion

1. Introduction

It is known that the visual system is capable of constructing illusory contours and color that may be absent in the physical stimulus (Grossberg, 1994; Kanizsa, 1979; Michotte, Thines, & Crabbe, 1964; Nakayama & Shimojo, 1990, 1992; Nakayama, Shimojo, & Ramachandran, 1990; Peterhans & von der Heydt, 1991; van Tuijl, 1975; Varin, 1971; Yamada, Fujita, & Masuda, 1993). Motion is especially effective in allowing the visual system to use multiple fragmented views of an object over time to reconstruct its shape as a whole (Andersen & Braunstein, 1983; Andersen & Cortese, 1989; Gibson, 1979; Kaplan, 1969; Lappin, Doner, & Kottas, 1980; Shipley & Kellman, 1993, 1994; Stappers, 1989; Ullman, 1979; Wallach & O'Connell, 1953; Wertheimer, 1923; Yonas, Craton, & Thompson, 1987). 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 the perception of subjective color, spreading into achromatic regions of the stimulus (see also Cicerone & Hoffman, 1992, 1997; Miyahara & Cicerone, 1997; Shipley & Kellman, 1994).

Here we report that stereoscopic depth, as well as color and form, can be fully recovered in tandem with seeing motion. We devised a modification of the CFM stimulus that introduced binocular disparity, defined solely by color, in the test region. In still binocular view of any pair of frames, rivalry occurs, due to the unmatched color of some of the corresponding image elements in the two eyes. However, when successive frames are rapidly cycled, left and right eye scenes are fused and a *colored* object is seen *moving in depth*. Furthermore, the perceived depth is consistent with the crossed or uncrossed disparity introduced into the test region. We propose that in natural scenes the same visual mechanisms may be used to reconstruct partially occluded objects so that their depth as well as color and form can be seen as if in plain view.

2. Methods

2.1. Observers

Data were collected on five observers. Observers A and B were the authors. All other observers were unaware of the design and the purpose of the experiment. Observer C was an emmetrope; all other observers wore optical corrections to 20/20. Observers were classified as color normal on the basis of Nagel anomaloscope matches.

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2.2. Apparatus, stimuli, and procedures

The stimulus used for Experiment 1 was similar to that used in previous studies (Cicerone & Hoffman, 1997; Cicerone et al., 1995; Miyahara & Cicerone, 1997). Each frame (Fig. 1a) was a square (8° in visual angle on a side, as viewed from a distance of 58 cm) over which was randomly arrayed 1200 dots (each 3.5 min of arc in diameter) whose locations are fixed from frame to frame. Within the 2° circular test region the dots were colored green (CIE $x = 0.280$, $y = 0.610$). All other dots were red (CIE $x = 0.621$, $y = 0.344$). The green test dot luminance was set at 9, 18, or 36 cd/m^2. The red surround dot luminance was set at 4.5, 6, 9, 12 or 18 cd/m^2. The background region was achromatic (CIE $x = 0.276$, $y = 0.286$) and of constant luminance (73 cd/m^2). To create successive frames, only the color assignments of some of the dots were changed; no dots changed their locations. The only change between successive frames was that the test region, the area in which all dots are colored green, was redefined by a uniform vertical displacement of 0.12° of visual angle. When frames are cycled with an effective displacement rate of the test region equivalent to 7°/s, over a vertical distance of 5° upward then 5° downward, an illusory green disk moving up and down pops into view and illusory color is seen in the physically achromatic regions of the test area (Fig. 1b). To obtain a quantitative measure of this effect, a physical light of complementary chromaticity was used to cancel the subjective color. The cancellation stimulus (Fig. 1c) was produced by varying the chromaticity of the background of the test region while keeping its luminance constant. Sitting in a darkened room, the observers were instructed to maintain fixation near the center of the display and to judge whether the background of the test region appeared "red" or "green". The experiment was self-paced with no fixed duration for each trial. A two-alternative, multiple-staircase procedure was employed. First, both the CFM stimulus and the cancellation stimulus were presented to both eyes. Next, the CFM stimulus was presented to both eyes, but the cancellation stimulus was presented to one eye only by means of an optical stereoscope.

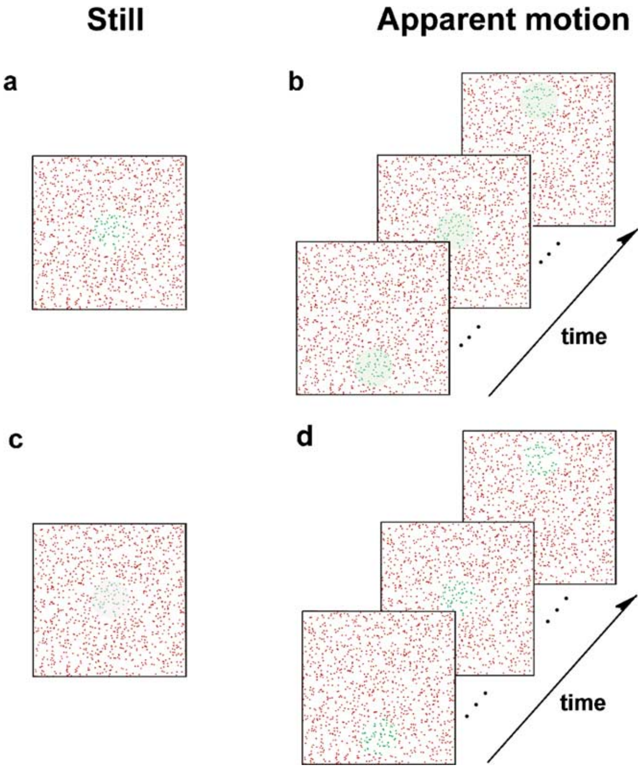

Fig. 1. Illustrations of the CFM stimuli used in Experiment 1. (a) A single frame of the CFM stimulus is shown. (b) When frames are cycled at a rate equivalent to 7°/s of apparent motion, color spread is seen, as illustrated here. (c) A single frame of the CFM stimulus with the cancellation stimulus applied to the test region. The cancellation stimulus is a physical light that looks reddish in still view. (d) In motion view, the test area appears achromatic.

In Experiment 2, we devised a modification of the CFM stimulus that produced binocular disparity by introducing mismatches in the colors assigned to corresponding image elements in the two eyes. Left and right eye views were identical in terms of the locations of all dots. Horizontal crossed or uncrossed disparities were created by color change alone; the test region—in which all dots were colored green—was reassigned laterally by 0.5° of visual angle. We emphasize that no dot changed its location; only changes in the color assignments of certain dots reflected the disparity. The green test dot luminance was fixed at 36 cd/m^2 and the red surround dot luminance set at 18 cd/m^2. Conditions with crossed or uncrossed horizontal displacement of the test region were randomly presented to the observers through the stereoscope. The observers were asked to judge whether the illusory figure defined by the subjective color spread lies *behind* or *in front* relative to the field of dots.

The conditions of Experiment 3 were identical to those of Experiment 2, except that the CFM stimulus was randomly presented only to one eye while the other eye was presented with a real green disk, comparable in luminance and saturation, and synchronous in movement to the illusory disk. All dots were red, and the achromatic background was identical to that of the CFM stimulus.

The stimuli were presented on a 21-in. Sony Trinitron CRT monitor driven by a Silicon Graphics Indigo II computer programmed with Open GL. The output luminances of the R, G, and B guns were measured (Photo Research model PR-650 Spectracolorimeter) and a gamma correction was applied to each gun individually to yield a linear function.

3. Results and discussion

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 (Day, 1983; Ehrenstein, 1941; Redies & Spillmann, 1981). Furthermore, subjective color spread as seen in CFM is not present in all motion stimuli; for example, it is not reported in kinetic occlusion (Andersen & Braunstein, 1983). 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. In fact, if the test region remains fixed in space and the dots themselves are set in random motion, no color spread is observed. It is interesting to note that although the perception of apparent motion appears to be essential for the perception of subjective color spread, effective speeds greater than 1° of visual angle per second produce little or no enhancement of the subjective color spread (Chen & Cicerone, 2002). Third, the luminance and the chromaticity of the dots in the region surrounding the test have no influence on the saturation or chromaticity of the subjective color spread as measured by cancellation (Chen & Cicerone, 2002). This is consistent with the view that CFM 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 (Chen & Cicerone, 2002; Miyahara & Cicerone, 1997). In this case, color itself, without a clearly perceived contour, represents the object.

Illusory color in CFM can be cancelled by a chromaticity change introduced into the test region (Fig. 2a) and, in that sense, is equivalent to a physical light. For Observers A and B, surround dot luminance, in the tested range, did not influence the physical light required to cancel the illusory color, whereas cancellation value increased as the luminance of the inner dots increased. When the color from motion stimulus was presented to both eyes, but the cancellation stimulus was presented through one eye only, observers reported a stable, unified scene without binocular rivalry and readily cancelled the illusory color (Fig. 2b). It is noted that the amount of physical light needed to cancel though one eye is roughly two times that required through both eyes for Observer A, but is greater than two for Observer C. For our purposes, the important issue is whether or not cancellation can be achieved at all via the presentation of the cancellation stimulus to one eye only.

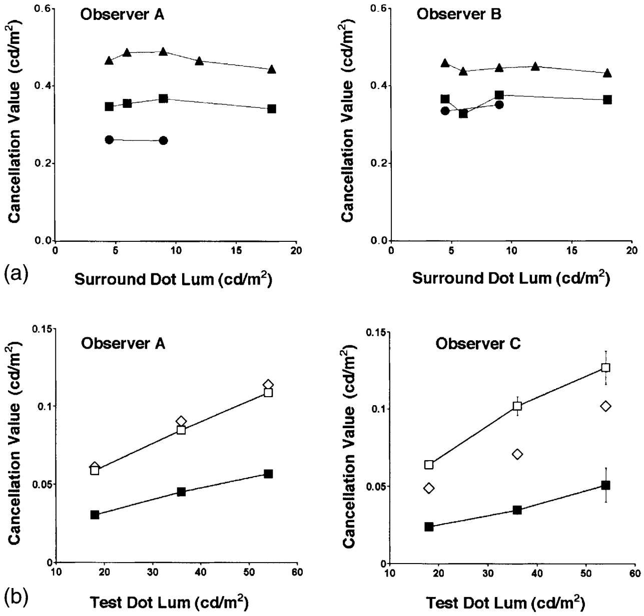

Fig. 2. Results of Experiment 1. (a) The cancellation values for Observers A (left) and B (right) are plotted as a function of surround dot luminance. Test dot luminance was set at 9 (circles), 18 (squares), or 36 (triangles) cd/m^2. (b) Results are plotted for Observers A (left) and C (right) when the cancellation stimulus is presented via one eye (open squares) or through both eyes (filled squares). Surround dot luminance was fixed at 18 cd/m^2. Test dot luminance was varied between 18 and 54 cd/m^2. The diamonds represent twice the value of the cancellation light when it is presented through both eyes.

In natural scenes, an object is often screened from full view by other elements lying in the foreground. Although certain parts of the object can be seen through gaps in the screening elements, often, neither the object, its color, nor its relative depth are perceived. Furthermore, dependent on the fixation plane, the color seen by the right eye may be different from that seen by the left eye through a particular aperture, as illustrated in Fig. 3a. In still view, because the object behind the screen is not perceived, conflicts in the color assignment to the same point in two-dimensional space for the left and right eye images, can result in binocular rivalry.

In the displays used for Experiment 2, the angular separation of the test region in left and right eyes was varied by horizontally displacing the definition of the test region in which dots are colored green. It is emphasized that, as in all other stimuli, the dot locations were unchanged from frame to frame and identical in both eyes. Due to the lateral displacement of the defined test region, certain dots in corresponding retinal locations in left and right eyes are green in the left eye view and red in the right eye view and vice versa (Fig. 3b). Despite the absence of color-matched image elements in the two eyes, can the illusory colored objects due to the separate monocular views be fused so that a unitary object is seen in depth?

When viewing single frames of this stimulus, observers report seeing either left or right eye views but not both at any instant (binocular rivalry), due to the mismatch in color of some corresponding elements. For

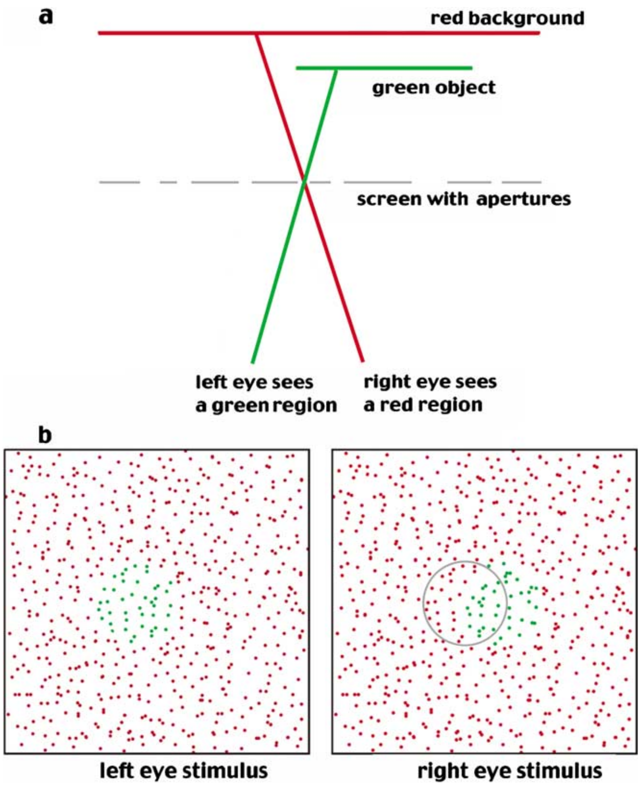

Fig. 3. The stimulus for Experiment 2. (a) As seen through apertures, parts of a visual scene imaged onto the left eye may be different from that imaged onto the right eye. (b) All dot locations are identical in left and right eye views. There is a 0.5° lateral displacement of the test region, defined solely by color, between left and right eye views. The green dots seen by the left eye (shown at the left and also indicated by the dark ring on the right) do not match the color of the dots in the corresponding region of the right eye view shown on the right. Therefore, binocular rivalry occurs in still view. With apparent motion, an illusory green object is seen to move either in front or behind the plane of the screen, consistent with the angular separation of the test regions in left and right eye views.

Table 1
Results of Experiment 2 are shown here for crossed and uncrossed disparities of 0.5° (judgment of depth in Experiment 2, percent correct)

	Crossed	Uncrossed
Observer A		
Still	42.5	47.5
Motion	95	92.5
Observer C		
Still	50	45
Motion	87.5	92.5
Observer D		
Still	55	60
Motion	100	100
Observer E		
Still	60	55
Motion	100	95

Each value is based on 40 trials. 95% confidence intervals were calculated for all values according to Newcombe's (1998) methods for proportions. Chance performance (50%) lies within the 95% confidence interval calculated for all values measured for still view. Chance performance lies well outside the 95% confidence interval for all values measured for motion view.

Table 2
Results of Experiment 3 are shown here for crossed and uncrossed disparities of 0.5° (judgment of depth in Experiment 3, percent correct)

	Crossed	Uncrossed
Observer A		
Still	45	35
Motion	100	95
Observer B		
Still	55	60
Motion	100	100

Each value is based on 40 trials. 95% confidence intervals were calculated for all values according to Newcombe's (1998) methods for proportions. Chance performance (50%) lies within the 95% confidence interval calculated for all values measured for still view. Chance performance lies well outside the 95% confidence interval for all values measured for motion view.

example, when the angular shift is greater than 1° of visual angle, less than a quarter of the green dots in the left eye stimulus are identical to those in the right eye stimulus (Fig. 3b). If either monocular view of the stimulus is viewed in motion, observers report seeing an illusory green disk moving up and down in the same plane as that of the dots. When the motion stimulus is viewed stereoscopically, observers report seeing a well-fused, illusory green disk moving *in depth*, in front of or behind the field of dots, consistent with the angular separation of the test regions in left and right eye stimuli. The perception of a single fused green disk occurs across a wide range of differential angular separations, from 0° to 2° for most observers. Four observers judged depth ("in front of" or "behind" the field of dots) with high accuracy if the stimulus was viewed in motion and at chance levels if the stimulus was the still view of single frames (Experiment 2, Table 1). In fact, observers are capable of seeing depth by fusing a real green disk presented to one eye with an illusory disk seen from the presentation of the CFM stimulus to the other eye (Experiment 3, Table 2). This indicates that the stereoscopic depth system treats the illusory disk as equivalent to a real disk. The perception of depth for the illusory figures is comparable to that for real figures in another way: There is a striking size illusion that accompanies the perception of depth in Experiments 2 and 3. If the green disk is seen to lie in front of the plane of dots, it appears to be smaller than if it is seen to lie behind. This perception, of a single, colored disk moving in depth, cannot be explained by element matching of right and left eye images, for example as in random dot stereograms (Julesz, 1971), because the group of dots colored green in the left eye view does not match the group of dots colored green in the right eye view.

In monocular view of the motion stimulus, all elements, the dots and the illusory moving disk, lie in the same plane—the scene is two-dimensional. In binocular view of the motion stimulus, an object lying in depth is perceived—the scene becomes three-dimensional. These results indicate that the visual system is capable of constructing three-dimensional scenes using binocularly displaced illusory objects that are due to separate monocular views distinguished solely by color differences in the image elements. Furthermore, that observers can fuse the illusory colored disks and that stereoscopic depth can be seen suggest that the visual system represents the illusory disk as separate from the image elements, the field of dots. We propose that analogous mechanisms may work in natural scenes, so that color changes and motion signals allow the human visual system to recover not form alone, but also the color and depth of objects that may be hidden from full view.

Acknowledgements

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