nature neuroscience

Color brings relief to human vision

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In natural scenes, chromatic variations, and the luminance variations that are aligned with them, mainly arise from surfaces such as flowers or painted objects. Pure or near-pure luminance variations, on the other hand, mainly arise from inhomogeneous illumination such as shadows or shading. Here, I provide evidence that knowledge of these color–luminance relationships is built into the machinery of the human visual system. When a pure-luminance grating is added to a differently oriented chromatic grating, the resulting 'plaid' appears to spring into three-dimensional relief, an example of 'shape-from-shading'. By psychophysical measurements, I found that the perception of shape-from-shading in the plaid was triggered when the chromatic and luminance gratings were not aligned, and suppressed when the gratings were aligned. This finding establishes a new role for color vision in determining the three-dimensional structure of an image: one that exploits the natural relationships that exist between color and luminance in the visual world.

The human visual system is highly sensitive to spatial variations in both luminance (light intensity) and color (light wavelength). There is considerable interest in the role of color vision in determining the chromatic (or spectral) content of a visual scene, as well as the structural (or form) content[1–15]. The principle method for studying the role of color vision in form perception is to use equiluminant (or isoluminant) stimuli: stimuli defined only by color variations. The rationale is that equiluminant stimuli will isolate the color vision system, enabling the experimenter to probe its properties directly[1–3,5–7,9,10]. Important clues to how color vision is involved in form perception may also emerge, however, from investigations of how color-sensitive and luminance-sensitive mechanisms interact when a subject is presented with stimuli that embody the particular relationships that exist between color and luminance in the natural visual world.

Consider, for example, a photograph showing a shadow that falls across a grass/pavement border (**Fig. 1**). The grass/pavement border has both color contrast (green to gray, left photograph) and luminance contrast (dark to bright, both photographs). The shadow border has mainly luminance contrast: although slightly bluer than its surround[14], the shadow has little visible color contrast. The photographs illustrate a general property of the color–luminance relationships found in natural scenes: color differences and spatially aligned luminance differences mainly arise from changes in surface reflectance (for example, dark green to light gray), whereas near-pure luminance differences mainly arise from inhomogeneous illumination, as in shadows[4,6,7,14].

Does the human visual system have knowledge of these color–luminance relationships built into its neural machinery? If so, our perception of the world should reflect this knowledge. The appearance of a stimulus known as a plaid provides compelling evidence of this built-in knowledge. When a left-oblique, luminance-defined grating (**Fig. 2a**) is superimposed on a right-oblique color-defined grating (**Fig. 2b**), the resulting plaid springs into three-dimensional (3D) relief (**Fig. 2c**). It is as if the plaid were a red-green material, such as a curtain, folded in depth and illuminated obliquely. The 3D impression is an example of 'shape-from-shading', a phenomenon that has hitherto been studied primarily in the achromatic domain[16–20]. That the critical stimulus arrangement for triggering the impression of depth is a luminance grating combined with a spatially non-aligned (in this case differently oriented) chromatic grating, is evidenced by the fact that when the two gratings are similarly oriented and fully aligned, observers report no depth (**Fig. 2d**). People also report little or no impression of depth when the plaids are defined solely by luminance or solely by color (**Fig. 2e,f**), indicating that the impression of depth is not a property of the plaid's structure *per se*. It would appear that color contrast can trigger the impression of 3D relief in luminance variations only when the color and luminance variations are spatially non-aligned, consistent with the idea that the visual system identifies chromatic variations with surfaces and pure-luminance variations with inhomogeneous illumination. I refer to the illusory depth in the plaid stimulus as the 'color-shading effect'.

To study the precise interplay among color, luminance and depth in the color-shading effect, I used an adjustable matching stimulus that had 'real' depth corrugations defined stereoscopically (**Fig. 3**). The matching stereo-grating had left-oblique depth corrugations of the same spatial frequency and orientation as the illusory depth corrugations in the plaid. Two naive observers, as well as the author, made adjustments of the amplitude of the corrugations in the stereo-grating until they matched those of the plaid, and these matched amplitudes were used as estimates of perceived depth.

The findings of the study can be summarized thus: color variations triggered the impression of depth when presented (i) at a different orientation to the left-oblique luminance grating or (ii) at the same orientation as but 'out-of-phase' with the left-oblique luminance grating. Adding color variations of the same orientation and 'in-phase' with the left-oblique luminance grating suppressed the impression of depth.

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Figure 1 Natural shadow in a color (left) and black-and-white (right) photograph.

experiment, it was the depth of the left-oblique corrugations in the plaid that was matched. Not unexpectedly, an increase in the luminance contrast of the left-oblique grating (whose depth was being matched) led to an increase in perceived depth (**Fig. 5**). What is interesting, however, is the effect of adding color contrast to the left-oblique grating: in this case it suppressed perceived depth, causing it to disappear after about 10%. Thus, when the chromatic variations were aligned with the luminance variations, color contrast suppressed the interpretation that the luminance variations arose from shading.

RESULTS

Non-aligned color variations trigger perceived depth

In the first experiment, the left-oblique grating (**Fig. 2a**) was fixed at 25% luminance contrast, and the right-oblique grating (**Fig. 2b**) was set to various combinations of color and luminance contrast. The color and luminance components of the mixed color-luminance, right-oblique grating were always perfectly aligned ('in-phase'), as in the example showing just the right-oblique grating (**Fig. 2d**). The results for the two naive observers (**Fig. 4**) (the author's settings were similar) show that the luminance contrast of the right-oblique grating had little effect on the perceived depth of the plaid's left-oblique corrugations. The presence of color contrast in the right-oblique grating, however, had a profound effect, causing perceived depth to increase rapidly after about 5%. In other words, color variations that were non-aligned with luminance variations promoted the interpretation that the luminance variations arose from shading.

Aligned color variations suppress perceived depth

In the second experiment, the right-oblique grating was fixed to 25% color contrast, and the left-oblique grating was presented with various combinations of color and luminance contrast. As in the previous

Out-of-phase color variations trigger perceived depth

In the third experiment, the color and luminance components in the left-oblique grating were always perfectly aligned, or in-phase. If one of the critical requirements for creating an impression of 3D relief is that the luminance variations defining shading are non-aligned with any chromatic variations that are present, one might expect that putting the color and luminance components of the shading pattern out of phase would restore the impression of depth. This prediction was tested using plaids in which the color and luminance components of the left-oblique grating were of various phase relationships (**Fig. 6**).

Introducing a phase offset triggered the impression of depth, with perceived depth peaking at a phase offset of a quarter of a cycle (at 90° and 270°; **Fig. 7**). In fact, one of the subjects (HW) reported a strong impression of depth in the out-of-phase condition, even when the right-oblique color grating was removed altogether.

DISCUSSION

It has been suggested that it would make good sense for the visual system to suppress luminance borders in favor of chromatic ones, as chromatic borders are more reliable indicators of surface boundaries[21]. The results of the present study add an important caveat to this idea, by showing that there are circumstances in which color contrast promotes luminance contrast for visual form judgments. Given that shadows and shading can be used by the visual system for object recognition[17], shape perception[16,18,22] and motion perception[23], it would make sense for the visual system to recruit color vision to help differentiate those luminance variations that are due to shadows and

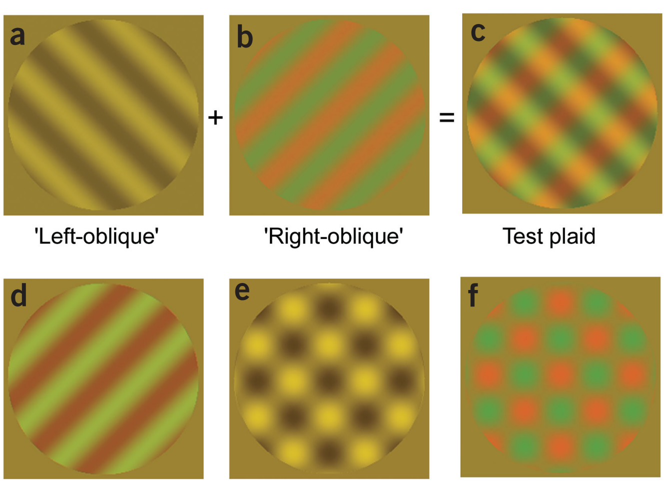

Figure 2 Shape-from-shading in plaid stimuli. The test plaid (**c**) is constructed by adding the left-oblique luminance grating (**a**) to the right-oblique, red-green color grating (**b**). For most observers, the plaid appears corrugated in depth, even though it is physically flat. Prolonged fixation of the plaid may result in some fading of one or both component gratings, with a temporary loss of depth. (**d**) The luminance and chromatic gratings are spatial aligned, or 'in-phase'. (**e**) The plaid is pure-luminance–defined. (**f**) The plaid is near-pure color-defined.

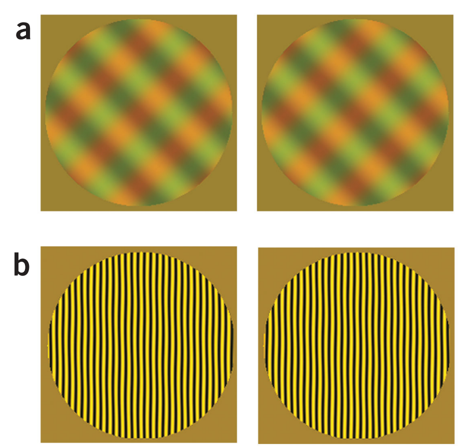

Figure 3 Stimulus arrangement for the measurement of perceived depth. (**a**) Test stereo-pair. Note there are no disparities between the two stereo-halves in the test stimulus, and any impression of depth in the fused image is due to shape-from-shading. (**b**) The two stereo-halves of the matching stereo-grating. When fused, the stereo-grating has left-oblique depth corrugations. Subjects were required to adjust the amplitude of these corrugations until they matched the perceived depth of the left-oblique corrugations in the plaid.

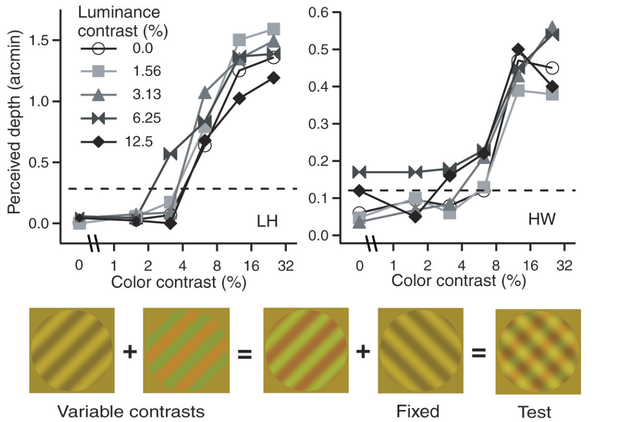

Figure 4 Stimulus manipulations (bottom) and results (top) for the first experiment. The luminance and color contrasts of the right-oblique grating were independently varied, and the pure-luminance, left-oblique grating was fixed in contrast. The graphs show perceived depth of the left-oblique corrugations as a function of the color and luminance contrast of the right-oblique grating. Different symbols, with different shades of gray, represent different luminance contrasts. The horizontal dashed line shows how much amplitude was needed to detect the depth corrugations in the matching stereo-grating, so points above this line represent a significant amount of perceived depth. Error bars have been omitted to avoid clutter.

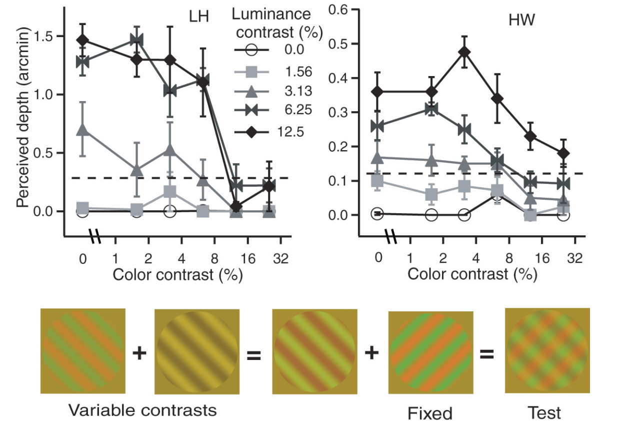

Figure 5 Stimulus manipulations and results for the second experiment. Perceived depth of the plaids' left-oblique corrugations is plotted as a function of the color and luminance contrast of the left-oblique grating. The pure-color, right-oblique grating was fixed in contrast.

shading from those that are due to changes in surface reflectance. The suppression of shape-from-shading by aligned chromatic variations is just the other side of the coin; the visual system makes the reasonable assumption that such luminance variations most likely originate from changes in surface reflectance.

The suppression of shape-from-shading by aligned chromatic variations, as reported here, may not hold for shape-from-shadows[22] where the shadows are defined by sharp edges. It may be that sine-wave plaids exemplify the situation in which the visual system has no cues other than the relationship between color and luminance to help parse the image into surface and illumination. It would be interesting to extend this work to more naturalistic objects to determine the precise circumstances in which color contrasts influence form judgments that are based on shadows and shading.

The modulation of shape-from-shading by the correlation between color and luminance contrast accords with the idea that the visual system has evolved to minimize the amount of redundant information in the neural image[24–26]. It also sits well with Bayesian (or probabilistic) approaches to visual function[27]. Considered within a Bayesian framework, the visual system seems to assign to each luminance discontinuity a probability that it arises from inhomogeneous illumination rather than reflectance, based in part on its spatial relationship with any color contrasts in the vicinity.

The findings of this study are also relevant to behavioral models of shape-from-shading. These have generally been restricted to an artificial world where the only luminance variations present are those arising from shading[19,20]. Such models will tend to fail with more naturalistic scenes where luminance changes due to surface-reflectance are confounded with those due to inhomogeneous illumination. These models might be made more successful if they included a stage in which color contrasts were detected and used as local weighting functions to strengthen uncorrelated luminance inputs (and weaken correlated inputs) to the shape-analysis stage.

Color vision is often considered the poor cousin of luminance vision in its capacity to analyze the third-dimension—depth[1,2,5–7,10]. For example, stereoscopic depth judgments of equiluminant stimuli, in which the test patterns vary only in color, are generally worse than with purely luminance-defined patterns[1,2,5,10]. The color-shading

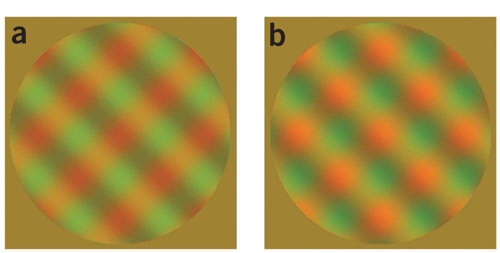

Figure 6 Plaids used in the third experiment. Each plaid consists of a right-oblique color grating and a mixed color-plus-luminance, left-oblique grating. (**a**) The color and luminance components of the left-oblique grating are in-phase (in perfect alignment). (**b**) They are 90° out of phase, or maximally out of alignment.

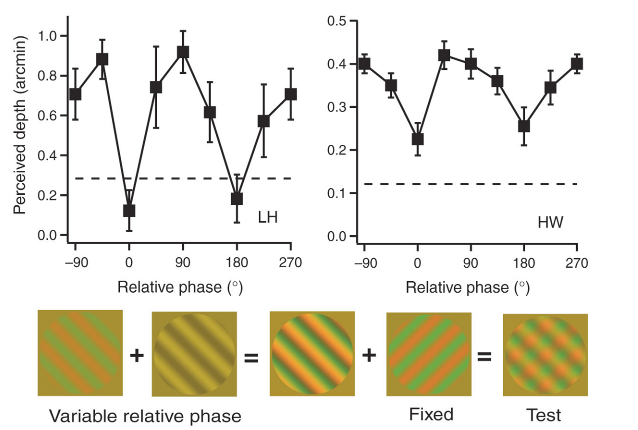

Figure 7 Stimulus manipulations and results for the third experiment. Perceived depth of left-oblique corrugations is plotted as a function of the relative phases of the color and luminance components of the left-oblique grating. The right-oblique grating was pure-color.

effect shows that color vision may, however, have a positive and perhaps unique role in analyzing the third dimension, through an interaction with luminance vision. This role of color vision in the analysis of 3D image structure complements the well-attested benefits of color vision in the analysis of 2D structure, as, for example, in the detection of fruits and flowers in dense foliage[8,11,13].

METHODS

Stimuli: plaids. All plaids were made from luminance and chromatic gratings that were combined additively. For the luminance gratings, the red and green phosphors of the monitor were modulated in-phase, and for the chromatic gratings in opposite phase. Grating contrast was defined as the Michelson contrast ($[L_{max} - L_{min}]/[L_{max} + L_{min}]$) of phosphor modulation, expressed in percent. The mean luminances (L) of the red and green modulations were adjusted for each subject to render the chromatic gratings ostensibly 'equiluminant', that is, only color-defined. For this we used the method of 'minimum motion'; subjects adjusted the relative mean luminances of the two components of a 25% contrast red–green grating drifting at 1 Hz, until perceived speed was at a minimum. The resulting equiluminant red-to-green ratios were 0.481 for LH and 0.484 for HW. The CIE coordinates (x, y) of the red and green phosphors were respectively (0.623, 0.34) and (0.278, 0.584). The gratings had a spatial frequency of 0.75 cpd (cycles per degree), and the plaids were presented in a circular hard-edged window of diameter 5°. The stimuli were generated using the VSG2/3F video-graphics card (Cambridge Research Systems) hosted by a standard Pentium-5 computer and displayed on a Barco Calibrator monitor. The two plaid gratings were presented on alternate frames of the monitor, which ran at 120 Hz.

Stimuli: matching stereo-grating. The stereo-grating used to match the perceived depth in the plaids consisted of two vertically oriented, 100% contrast, sinusoidal luminance gratings, with a spatial frequency of 6 cpd for subject HW and 3.0 cpd for subject LH. Depth corrugations were introduced by making the luminance bars of the stereo-grating oscillate sinusoidally from left to right as they descended from the top of the pattern, the oscillation being of opposite phase in the two stereo-halves. To make the depth corrugations left-oblique, the phase of oscillation was shifted from one bar to the next by $2\pi f_c/f_m$, where f_c was the spatial frequency of the depth corrugations (that is, the same as the gratings in the plaid – 0.75 cpd) and f_m was the spatial frequency of the luminance bars in the stereo-grating (see above). The amplitude of the oscillation determined the amplitude of the depth corrugations, and the measure of perceived depth was defined as twice this amplitude expressed in minutes of visual angle (arcmin). Viewing distance to the display along the light path through the stereoscope was 105 cm.

Procedure. Subjects used the keys on a response box (Cambridge Research Systems) to adjust the amplitude of the depth corrugations in the stereo-grating until they matched those in the plaid. There was no time limit. Some subjects experienced fading of one or other of the gratings in the plaid during prolonged fixation, and subjects were therefore encouraged to let their eyes roam around the stimuli and alternate between the plaid and stereo-grating. During each experimental session, all the conditions of an experiment were presented in random order, and for each experiment there were six repeat sessions, producing six measurements per condition. Written consent was obtained from all test subjects, and the experimental protocols were approved by the McGill University Research Ethics Board.

ACKNOWLEDGMENTS
This research was supported by a Canadian Institute of Health Research grant (MOP-11554 to F.K.). Special thanks to D. Field and K. Mullen for suggestions on an earlier version of the manuscript.

COMPETING INTERESTS STATEMENT
The authors declare that they have no competing financial interests.

Received 17 December 2002; accepted 1 April 2003
Published online 12 May 2003; doi:10.1038/nn1060

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