

# Detection of contrary chromatic change

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In visual search experiments we examined whether targets that are distinguished from distracting items solely by a contrary change in color can be sought spatially in parallel. Targets under time-varying illumination pop out if they present a contrary luminance signal; targets under space-varying illumination can be detected in parallel when they are isoluminant. The results suggest that neurons with spatially and chromatically opposed receptive fields are active across the central visual field.

## INTRODUCTION

Recent research on color constancy<sup>1-4</sup> draws an analogy between color and structure from motion.<sup>5</sup> A set of surfaces with steady reflectance properties presents a rigid color structure through reflected lights. A change in illumination provides a second view of these surfaces. If one can track particular surfaces through the change in illumination, which is an assumption of surface correspondence, then one can, in principle, recover accurate descriptions of surface reflectance properties from the change in quantum catches caused by the change in illumination.

We wondered whether the lights from surfaces that are viewed under changing illumination provide a chromatic structure against which contrary chromatic change is readily detected. In the case of structure from motion a broad class of nonrigid motions do pop out. An observer perceives nonrigidity instantly, for instance, if one of the eight corners of a rotating cube suddenly moves in an odd way in an otherwise rigid display. In the case of surface color one might ask, by analogy, the following: if the illumination changes so that lights reflected from surfaces become yellower, will a solitary patch of light that becomes bluer pop out? We describe here the results of visual search experiments<sup>6,7</sup> that were designed to determine the conditions under which observers readily detect contrary chromatic change.

## METHODS

Lit surfaces were simulated with a DECstation computer and a Sony color television monitor. Background and distractor surfaces with fixed reflectance properties provided coherent chromatic change when they were viewed under sinusoidally modulated illumination. Light from the target surface was made to oscillate in counterphase to provide its contrary change. The simulated illumination was modulated between the Commission Internationale de l'Éclairage (CIE) daylight standard D<sub>65</sub> and the CIE fluorescent standard F<sub>2</sub>.<sup>8</sup>

We performed two types of experiment: those in which the illumination was modulated in *time* to cause a 6 × 6 square grid of simulated Munsell chip papers to flicker at 2 Hz (see Fig. 1A) and those in which the illumination was

modulated in *space* to cause lights from an array of 20 adjacent horizontal strips of simulated Munsell chip papers to undulate chromatically at 0.7 cycle/deg along the horizontal dimension of the display (see Fig. 1B). The background in both experiments simulated the reflectance properties of the neutral gray chip N5; the target also simulated N5 but was modulated in counterphase (see Fig. 2). The intensity of the simulated illuminant F<sub>2</sub> relative to that of D<sub>65</sub> could be varied to make the target modulation either an isoluminant one or a nonisoluminant one.

Distracting items were chosen from a set of six simulated Munsell chips; their illumination was modulated in phase with that of the background to provide coherent chromatic change. Distractors were chosen to mask the target. The target was at no time or location distinguished by an extreme chromaticity or, in cases in which illuminant intensities were chosen to make the target isoluminant, by its intensity.

In the experiments with time-varying illumination, observers sought the target, present in half of the trials, within displays of 1, 9, 18, or 36 items presented at random positions in the 6 × 6 grid; the modulated background appeared in positions not taken by the target or the distractors. In the experiments with space-varying illumination, observers sought the target within displays of 1, 6, 12, or 18 items presented at random positions within the display of 20 strips, with the exception of the strips at extreme top and bottom, which were occupied in all the displays by the modulated background.

The task was to respond as rapidly as possible whether the target was present or absent by pressing an appropriate key. Immediately following a response the display was replaced by the background surface lit steadily by the average of the two illuminants, and either one beep (target present) or two beeps (target absent) sounded to provide indirect feedback.

## RESULTS

The results of the experiments with time-varying illumination for two observers (the authors) are presented in Fig. 3A in terms of the slopes of the best-fitting lines to the reaction times, for target-present (open circles) and target-absent (solid circles) trials, determined as a func-

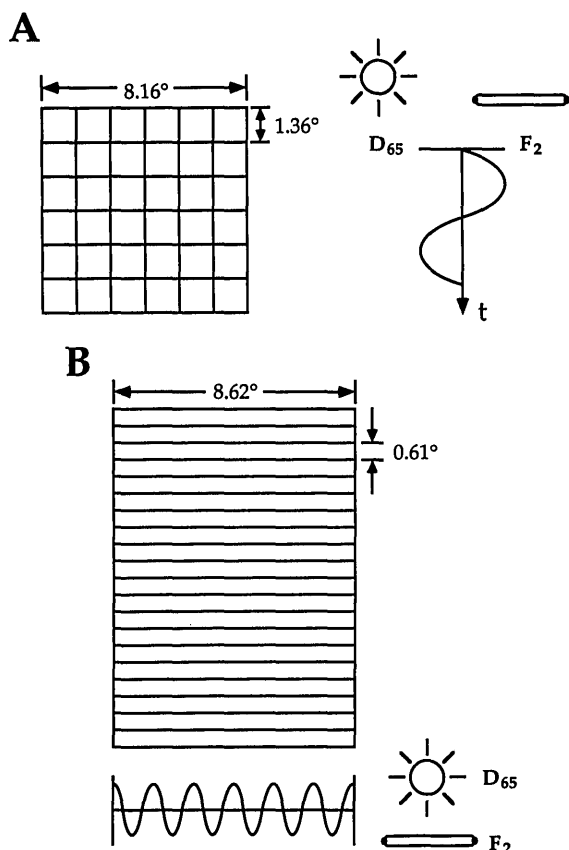


Fig. 1. A, A  $6 \times 6$  square array of simulated Munsell chip papers centered on a black surround, where the side of each square subtended  $1.36^\circ$  of visual angle to produce an  $8.16^\circ \times 8.16^\circ$  stimulus area, was modulated sinusoidally in time at 2 Hz through a simulated oscillation of illumination between  $D_{65}$  and  $F_2$ . B, Each of 20 adjacent strips of simulated Munsell chip papers, centered on a black surround, had a width of  $0.61^\circ$  of visual angle and a length of  $8.62^\circ$ , producing a stimulus area  $8.62^\circ$  wide by  $12.2^\circ$  long. The strips were modulated sinusoidally, through a simulated oscillation of illumination between  $D_{65}$  and  $F_2$ , across the horizontal extent of the display. The spatial frequency of the oscillation was 0.7 cycle/deg, so producing six full cycles.

tion of number of displayed items. These slopes are shown for seven choices of relative illuminant intensity that caused the target to present counterphase luminance flicker of 20%, 10%, 5%, and 0% contrast relative to the background in cases in which the simulated illuminant  $F_2$  was relatively brighter (positive contrasts) and relatively darker (negative contrasts).

Reaction times are independent of the number of items—indicated by a slope of zero—only in cases in which counterphase luminance flicker of sufficient contrast is present ( $\pm 20\%$ ). Targets distinguished by contrary luminance motion pop out. The targets did not pop out near and at isoluminance (0%), as indicated by the positive slopes of approximately 15 and 30 ms/item for target-present and target-absent trials, respectively. The target resembles a slowly flickering light when a sufficiently large luminance contrast is present.

The results suggest that time-varying contrary chromatic changes, when they are masked thoroughly in chromatic attributes, pop out only if they present a contrary luminance signal. Counterphase luminance flicker pops

out, while chromatically masked counterphase flicker at isoluminance does not.

Results with space-varying illumination are displayed in Fig. 3B; these show that observers detected the targets spatially in parallel, both in cases in which a counterphase luminance signal was present and in the isoluminant case (0%), in which the target was distinguished solely by its contrary chromatic change at isoluminance. Observers found the isoluminant target not through attention to color—the target was masked thoroughly in its color attributes—but through attention to a spatial checkerboarding of the display that appeared on trials in which the target was present. On close inspection the target

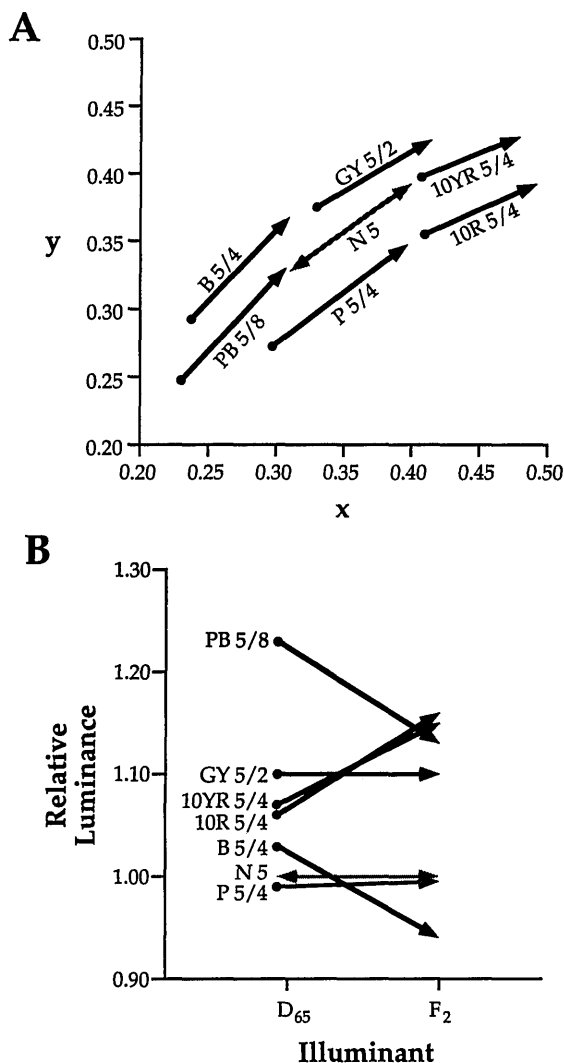


Fig. 2. A, CIE 1931  $(x, y)$  chromaticities and Munsell chip designations of the background (gray arrow) and the distractors, modulated in phase by illumination varying between  $D_{65}$  (arrow base) and  $F_2$  (arrowhead), and the counterphase modulated target (gray arrow, reverse direction). In a control experiment with space-varying stimuli the target was modulated in phase with the distractors, while the background items were modulated in counterphase. B, Normalized luminances of the background, the distractors, and the target. The relative value 1.0 corresponds to an absolute luminance of  $7 \text{ cd/m}^2$  on a Sony GDM 1602 monitor for the time-varying experiments and to an absolute luminance of  $16 \text{ cd/m}^2$  on a Sony GDM 1960 monitor for the space-varying experiments. At no one time or location was the target distinguished by either color or brightness when it was presented at isoluminance: the target is not distinguished by a trivial color cue.

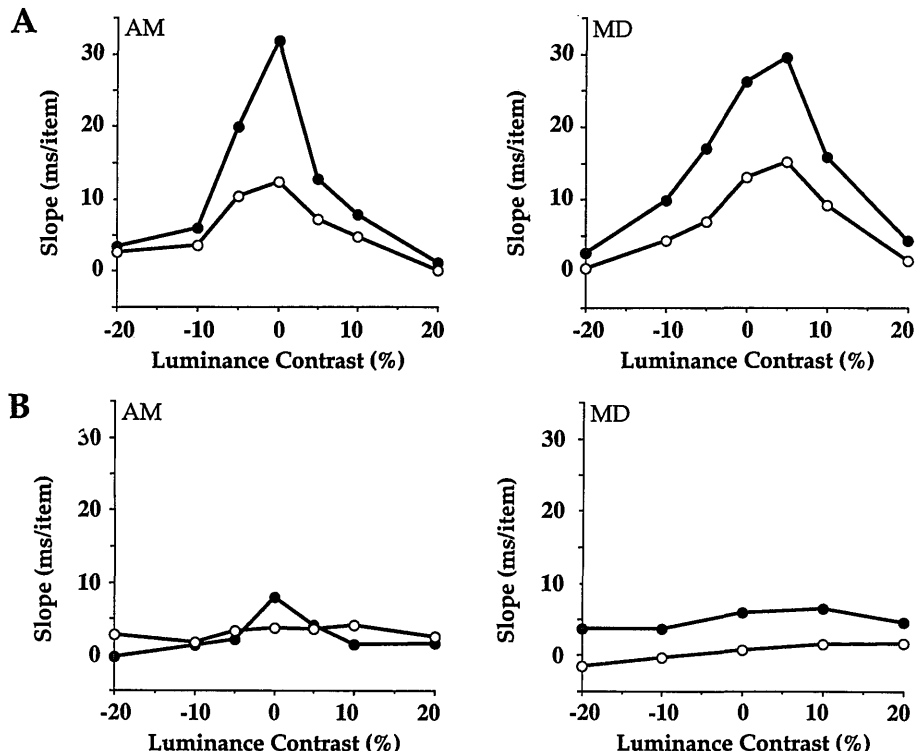


Fig. 3. A, Slopes of the best-fitting lines to graphs of reaction time versus number of displayed items for target-present trials (open circles) and target-absent trials (solid circles) for two observers in the experiments with time-varying illumination. The observers' ability to detect in parallel targets that present counterphase luminance modulation, indicated by the near-zero slopes at  $\pm 20\%$  contrast, deteriorates at isoluminance (0% contrast). The average percentages correct for observers AM and MD were 95.5 and 93.2, respectively. The average intercepts of the best-fitting lines to target-present trial data for AM and MD were 516 and 500 ms, respectively. B, Slopes from the experiments with space-varying illumination are nearly zero in both isoluminant and nonisoluminant conditions. The average percentages correct for AM and MD were 96.2 and 94.2, respectively. The average intercepts of the best-fitting lines to target-present trial data for AM and MD were 380 and 389 ms, respectively. All the slopes are computed from reaction-time results at four levels of the variable number of displayed items from 60 trials, preceded by 40 unscored practice trials.

typically resembles a strip of varying color (viz., changing surface reflectance).

We performed a control experiment to test whether the parallel-search result for the space-varying stimuli at isoluminance is caused by contrary chromatic change. We modulated the isoluminant target in phase with the distractors, and together these were modulated in counterphase to the background (see Fig. 2A). The result is that the target is no longer distinguished from distracting items by contrary chromatic change; rather, the target is distinguished by its space-averaged chromatic content (i.e., gray target versus colored distractors). If parallel search relies on contrary chromatic change, then one should find that parallel search is impossible in the control condition.

The slopes of the best-fitting lines to the reaction times in the control experiment were, for target-present and target-absent trials, 135 and 240 ms/item for observer AM, respectively, and 116 and 244 ms/item for observer MD, respectively. These slopes, taken with the near-zero slopes at isoluminance in the basic experiment (Fig. 3B), suggest strongly that contrary chromatic change is needed for parallel search in the space-varying case.

## DISCUSSION

Parallel search at isoluminance for space-varying contrary chromatic change suggests the activity of mecha-

nisms with receptive fields that are inseparable in their spatial and chromatic properties. Double-opponent units distributed across the central visual field are possible candidates.<sup>9,10</sup> The increase in reaction time with number of items at isoluminance in the time-varying case, on the other hand, is roughly consistent with known results on the perception of motion. The target presents a flicker signal that can be decomposed as a sum of traveling waves, some diverging from the target and some converging toward the target. The traveling waves provide a poor motion stimulus at isoluminance<sup>11</sup> but otherwise provide a readily detectable signal.

Visual stimuli that move in similar ways are often perceived as a single structure, according to the Gestalt principle of common fate.<sup>12</sup> Such a structure can serve as a visual figure, within which particular items may be sought, or may serve as a background, against which a stimulus with contrary motion is detected.<sup>13</sup> We ask, by analogy, whether stimuli that undergo similar chromatic changes are perceived as a single structure and, in particular, whether a stimulus that undergoes a contrary chromatic change is readily detected. A natural way to cause a coherent change in chromatic properties is to change a scene's illuminant: reflected lights will change in similar ways.

The results suggest that surfaces with steady reflectance properties can underlie perceptual structures that can serve as backgrounds, against which a stimulus that

possesses a contrary chromatic change is readily detected. Natural stimuli that provide contrary chromatic change include surfaces that have changing reflectances, surfaces lit by different sources of illumination, and even light sources.<sup>14</sup> The results also hint at why the failures of the human faculty for color constancy are not often noticed in natural situations. We have in mind the failures that are documented in experiments wherein observers must focus attention on changes in surface color appearance that occur when illuminant color is changed (e.g., Refs. 15 and 16). The failures of color constancy that are noticed in natural viewing are rare because they must pop out to be noticed. It is far more common for the visual system to respond to contrary chromatic change by assigning correct physical interpretations to surfaces with changing reflectance, surfaces lit by different sources of illumination, light sources, and the like, and this performance is perhaps best characterized through natural detection tasks.

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## REFERENCES

1. M. D'Zmura, "Color constancy: surface color from changing illumination," *J. Opt. Soc. Am. A* **9**, 490-493 (1992).
2. M. D'Zmura and G. Iverson, "Color constancy: adaptation to the illumination environment," in *Advances in Color Vision*, Vol. 4 of the OSA 1992 Technical Digest Series (Optical Society of America, Washington, D.C., 1992), pp. 107-109.
3. M. D'Zmura and G. Iverson, "Color constancy. I. Basic theory of two-stage linear recovery of spectral descriptions for lights and surfaces," *J. Opt. Soc. Am. A* **10**, 2148-2165 (1993).
4. M. D'Zmura and G. Iverson, "Color constancy. II. Results for two-stage linear recovery of spectral descriptions for lights and surfaces," *J. Opt. Soc. Am. A* **10**, 2166-2180 (1993).
5. S. Ullman, "The interpretation of structure from motion," *Proc. R. Soc. London B* **203**, 405-426 (1979).
6. A. Treisman, "Preattentive processing in vision," *Comput. Vision Graphics Image Process.* **31**, 156-177 (1985).
7. M. D'Zmura, "Color in visual search," *Vision Res.* **31**, 951-966 (1991).
8. G. Wyszecki and W. S. Stiles, *Color Science. Concepts and Methods, Quantitative Data and Formulas*, 2nd ed. (Wiley, New York, 1982).
9. C. R. Michael, "Color vision mechanisms in monkey striate cortex: dual-opponent cells with concentric receptive fields," *J. Neurophysiol.* **41**, 572-588 (1978).
10. M. S. Livingstone and D. H. Hubel, "Anatomy and physiology of a color system in primate primary visual cortex," *J. Neurosci.* **4**, 309-356 (1984).
11. P. Cavanagh, C. W. Tyler, and O. E. Favreau, "Perceived velocity of moving chromatic gratings," *J. Opt. Soc. Am. A* **1**, 893-899 (1984).
12. M. Wertheimer, "Principles of perceptual organization," in *Readings in Perception*, D. C. Beardslee and M. Wertheimer, eds. (Van Nostrand, Princeton, N.J., 1958), pp. 115-135.
13. K. Nakayama and G. H. Silverman, "Serial and parallel processing of visual feature conjunctions," *Nature (London)* **320**, 264-265 (1986).
14. S. Ullman, "On visual detection of light sources," *Biol. Cybern.* **21**, 205-212 (1976).
15. J. J. McCann, S. P. McKee, and T. H. Taylor, "Quantitative studies in retinex theory. A comparison between theoretical predictions and observer responses to the 'color mondrian' experiments," *Vision Res.* **16**, 445-458 (1976).
16. L. E. Arend, Jr., and A. Reeves, "Simultaneous color constancy," *J. Opt. Soc. Am. A* **3**, 1743-1751 (1986).