Color search and visual field segregation

MICHAEL D'ZMURA

University of California, Irvine, California

PETER LENNIE

University of Rochester, Rochester, New York

and

CARLO TIANA

FLIR Systems, Portland, Oregon

Visual search for targets that combine color and shape features that are shared by distracting items can be conducted spatially in parallel. Experimental results show that parallel search for color/shape conjunctions is possible when the shapes chosen let observers segregate the spatially interspersed items into figure and ground and when, within the figure, the target differs from other items by a distinguishing color feature. Results of experiments that manipulate stimulus color suggest that adaptive mechanisms of color discrimination are used to detect targets within such a figure.

How do we use color information to help find things? One way is to select a visual detection mechanism with a spectral sensitivity that is most appropriate to the task (D'Zmura, 1991). Observers try to maximize their spectral sensitivity to the color of the thing being sought and simultaneously minimize their sensitivity to the colors of distracting items. This optimal spectral sensitivity need not correspond to one of the standard red, yellow, green, and blue of color opponent theory (Hurvich & Jameson, 1955, 1957; Jameson & Hurvich, 1955) but may correspond to an arbitrary, intermediate hue such as orange or violet. Search for an orange target, for instance, can be mediated directly by an "orange" detection mechanism rather than through probability summation of "red" and "yellow" mechanism responses.

Experimental results from the visual search paradigm of Treisman and colleagues (Treisman, 1985; Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977) suggest that one can successfully search for a colored target spatially in parallel if there is a chromatically linear mechanism with a sufficiently high signal-to-noise ratio (D'Zmura, 1991). A threshold on the response of such a linear detection mechanism is represented by a plane in a three-dimensional color space related linearly to cone photoreceptor responses or by a line in a chromaticity plane (Wyszecki & Stiles, 1982). Thus, search can be con-

ducted in parallel if there is a line in the chromaticity plane that separates target from distractor chromaticities.

Recent work by Bauer, Jolicoeur, and Cowan (1996) has replicated and extended these findings through an examination of just how distinguishable target and distractor chromaticities must be for detection to operate spatially in parallel (see also Nagy & Sanchez, 1990). Bauer and colleagues have shown that spectrally nonlinear mechanisms, too, can mediate parallel search when the target chromaticity is highly distinguishable from the distractor chromaticities.

The purpose of the experiments reported in this paper was to identify the level of visual processing at which such color detection mechanisms operate. Early accounts of preattentive visual processing suggested that several color manifolds (e.g., red, yellow, green, and blue feature maps) provide early processing of color information in visual search (e.g., Treisman, 1985; Treisman & Gormican, 1988). However, the adaptive discrimination of color demonstrated in visual search experiments suggests that the detection mechanisms operate on more fully processed representations of the visual field (D'Zmura, 1991). Further results suggest that surfaces with stable color reflectance properties can underlie perceptual structures that can serve as grounds against which a stimulus that undergoes a contrary chromatic change is readily detected (Craven & Foster, 1992; D'Zmura & Mangalick, 1994). Our results here on parallel search for conjunctions of color and shape show that color detection mechanisms operate on visual information that has been segregated into figure and ground.

In the present experiments, we used colored disks shaded like those used by Ramachandran (1988a, 1988b) in studies of shape from shading. He presented achromatic disks that were brightest either at their tops or at their bottoms. Disks that were brightest at their tops appeared

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convex (viz., protruded from the background), whereas disks that were brightest at their bottoms appeared concave. Ramachandran showed that it was easy to segregate the convex from the concave disks in displays in which many such disks were placed randomly. In related work, Enns and Rensink (1990) used a visual search paradigm to show that one can search spatially in parallel for a convex target among concave distractors.

The results of the present experiments show, first, that color/shape conjunctions may be sought spatially in parallel. A red convex target, for instance, is readily found when presented among red concave and green convex distractors. They also show that search is hindered if the stimuli are altered in ways that degrade their segregability. Finally, the present results suggest that adaptive mechanisms of color detection operate on information provided by mechanisms of segregation. A preliminary version of this work, and a replication of Nakayama and Silverman's report (1986a) on parallel search for color/motion conjunctions, have been presented elsewhere (D'Zmura, 1990; Tiana, Lennie, & D'Zmura, 1989).

METHOD

Stimuli were presented on a Sony Trinitron GDM-1950 RGB monitor viewed binocularly at a distance of 1.4 m in a dark room. An area of 8.5×8.5 square degrees of visual angle in the center of the screen provided a steady, neutral gray background with luminance 20.3 cd/m^2 and CIE 1931 (x, y) chromaticity (.284, .286) (Wysecki & Stiles, 1982). The surrounding area was black. Color video signals were generated by a Pixar II image computer that displayed 768×768 pixels in the background area at 60 Hz (noninterlaced). This computer transmitted 30 bits of chromatic information per pixel to the color monitor, 10 bits per gun. The luminance and chromatic properties of the display were calibrated with a Minolta ChromaMeter.

A Sun 3/280 host controlled the stimulus presentation. Each experimental run had four blocks of 40 trials. In a single block, eight conditions were each presented in random order five times: (1, 8, 16, 32 displayed items) by (target present, absent). On target-present trials with $n > 1$ displayed items, the display contained $n/2$ and $n/2 - 1$ instances of two types of distractors; the two values were assigned randomly to distractor type across trials. On target-absent trials with more than one displayed item, equal numbers of the two types of distractors were displayed; for single-item trials, the distractor was assigned randomly.

Targets and distractors were disks of diameter 0.89° (81 pixels) with a mean luminance that matched that of the neutral background. The disks were placed randomly on a 6×6 square lattice ($\Delta x = \Delta y = 1.41^\circ$) of locations, centered on the background, from which the corners had been removed. The positions of the disks on this regular array of 32 possible locations were perturbed by noise that was drawn from a radially symmetric uniform density that allowed a maximal excursion of 0.22° .

Each trial started with a "reminder" interval lasting 1 sec, whose onset was signaled by a brief tone (beep), during which the target disk was displayed at a random location within the background area. The target then disappeared. After 1 sec, two further beeps sounded at an interval of 1 sec, followed 1 sec later by the target/distractor display. The display disappeared promptly after the observer signaled either the presence or the absence of the target; .5 sec later, a signal indicated whether the target had been present (two beeps) or absent (four beeps).

Observers used a keyboard to signal either the presence (with dominant hand) or the absence of the target. The clock provided by

the Sun's operating system (SunOS 3.5) resolved intervals to 20 msec, which, although initially a cause of concern, proved adequate.

The authors served as the observers. M.D. and P.L. had prior experience in visual search experiments; C.T. had none. Each observer ran at least three times in each experiment; all but the last two runs served as practice. Results from the initial blocks of these two runs were ignored, so that an observer's data for each condition are drawn from six blocks of trials. Performance among the 3 observers was very similar in all experiments except for the last; except in Table 1 and in the results from the last experiment, the reaction times below are presented as averages of the 3 observers' mean reaction times.

RESULTS

Search Among Shaded Objects

In a first experiment, we examined whether search for color/shape conjunctions is conducted in parallel under optimal shading conditions. We used disks that were either a desaturated red, with chromaticity coordinates (.293, .282), or a desaturated blue green (.274, .289) (see Figure 1). The disks were shaded by a linear, vertical gradient of brightness using a high-contrast (90%) ramp; the mean luminance of all disks matched that of the neutral gray background. The red target and blue-green distractor disks were shaded to be brightest at their tops (apparently convex), and the red distractors were shaded to be brightest at their bottoms (apparently concave). The red distractors were identical to the red target rotated through 180° .

Figure 2 shows the mean reaction times for target-present and target-absent trials, marked by the unfilled and filled circles ("Top/Bottom"), respectively. The slope of the best fit straight line to the target-present reaction times is only 1.1 msec/item; that to the target-absent reaction times is 3.1 msec/item. There is no significant linear dependence of reaction time on number of displayed items for either the target-present [$F(1, 10) = 0.37, p \leq .55$] or the target-absent [$F(1, 10) = 1.3, p \leq .28$] trials, in agreement with observers' reports that the color/shape conjunction "popped out." This performance level was reached rapidly by the observers, as shown in Table 1, which lists for the first three experimental runs the slopes of the best fit lines to the reaction times of each observer for target-present and target-absent trials. These data suggest that practice played little role in the result.

Table 1
Effects of Practice on the Slopes of the Best Fit Lines to Each Observer's Reaction Times for Target-Present and Target-Absent Trials in the Top/Bottom Shaded Disk Experiment

Run	Observer					
	M.D.		P.L.		C.T.	
	Target Present	Target Absent	Target Present	Target Absent	Target Present	Target Absent
1	1.2	4.0	-0.9	6.4	3.4	9.5
2	0.4	1.7	-2.8	3.9	2.6	1.9
3	0.9	2.1	2.2	1.8	1.9	4.6

Note—Entries in milliseconds/item are shown for the first three experimental runs, each of which comprised 160 trials, of which the first 40 were discarded in analysis.

Figure 1. The red convex target is readily found when presented among red concave and green convex distractors.

Effects of Shading Orientation

If the parallel-search result depends on the ease with which convex and concave disks are segregated, search should be hindered by manipulating shading in ways that reduces such segregability. Several control experiments to test this were conducted. The first manipulation, run in tandem with the initial parallel-search condition, involved the effects of shading orientation. Ramachandran (1988a, 1988b) showed that stable differences in the appearance of apparently convex and concave disks could be reduced by rotating the disks through 90° , making them brightest at either their left- or their rightmost borders. This manipulation diminishes the apparent convexity or concavity of the disks and hinders the segregation of the array into figure and ground items. If the parallel search for the red convex disk exploits segregability, search will be more difficult if the disks of the first experiment are rotated through 90° .

The red target and blue-green distractor disks were shaded to be brightest at the right, the red distractors brightest at the left. Reaction times for the high-contrast, right/left shaded disks are shown in Figure 2 by the squares (target-present, open; target-absent, filled). The slope of the best fit line to the target-present reaction times is 8.6 msec/item; that to the target-absent reaction times is 18.2 msec/item. In both cases, there is a significant lin-

ear dependence of reaction time on number of displayed items [target-present, $F(1,10) = 16.1$, $p \leq .0025$; target-absent, $F(1,10) = 10.5$, $p \leq .0089$].

Presenting the disks in an orientation that reduces their segregability hinders search for the target. A two-way analysis of variance for within-subjects factors of orientation (top/bottom vs. right/left) and number of displayed items (1, 8, 16, 32) for target-present trials showed the significance of orientation [$F(1,2) = 94.9$, $p \leq .01$], number of displayed items [$F(3,6) = 13.1$, $p \leq .0048$], and the interaction between orientation and number of displayed items [$F(3,6) = 11.3$, $p \leq .0071$].

Effects of Shading Contrast

The second manipulation of shading involved the effects of contrast. Informal observations suggested that reducing the contrast of the luminance gradients of the disks reduced their apparent convexity or concavity. Experiments were performed with disks with low-contrast luminance gradients, in order to determine whether reductions in shading contrast would hinder search.

Red target and blue-green distractor disks were shaded to be brightest at their tops, and the red distractors were shaded to be brightest at their bottoms, as in the initial experiment. Mean reaction times for conditions in which the disks were of 20%, 10%, or 5% contrast are shown in Fig-

Figure 2. Means of the observers' reaction times for top/bottom and right/left experiments with high-contrast shaded disks, plotted as a function of the number of items in the display. Results for target-present trials are indicated by open symbols and for target-absent trials by filled symbols. Circles mark the mean reaction times in the search for a red disk brightest at the top (convex) among blue-green disks brightest at the top (convex) and red disks brightest at the bottom (concave): search is parallel. Squares refer to the search for a red shaded disk brightest at the right among blue-green disks brightest at the right and red disks brightest at the left. Rotating the top/bottom disks through 90° hinders search. Percent correct rates in the top/bottom and right/left experiments were 96 and 97, respectively. Error bars shown for target-present trial results show the standard error of the mean for the 3 observers. See text for discussion.

ure 3 by the circles, squares, and triangles, respectively; only the results from target-present trials are shown. The slope of the best fit straight line to the target-present reaction times for the 20% contrast results is only 1.3 msec/item [$F(1,10) = 1.81, p \leq .21$]; that to the target-absent reaction times (not shown) is 3.7 msec/item [$F(1,10) = 6.65, p \leq .028$]. The slopes of the best fit lines to the target-present reaction times for the disks at 10% and 5% contrast are 3.2 [$F(1,10) = 4.0, p \leq .073$] and 5.1 [$F(1,10) = 26.8, p \leq .0004$], respectively; those to the target-absent reaction times (not shown) are 9.1 [$F(1,10) = 11.1, p \leq .0076$] and 13.9 [$F(1,10) = 48.0, p \leq .00005$], respectively.

We attempted to incorporate a fourth condition in this experiment that used disks with a contrast of 2.5%. The task at this contrast was very difficult—convex and concave disks were hard to distinguish—and it produced results with unacceptably high error rates.

Search is progressively but modestly hindered by reducing contrast from 20% to 5%. A two-way analysis of variance for within-subjects factors of contrast (0.05, 0.1, 0.2) and number of displayed items (1, 8, 16, 32) for target-present trials showed the significance of contrast [$F(2,4) = 9.8, p \leq .029$], number of displayed items [$F(3,6) = 57.3, p \leq .0001$], and the interaction between contrast and number of displayed items [$F(6,12) = 7.9, p \leq .0013$].

Elimination of Shading Cues

The foregoing manipulations of orientation and contrast reduced but did not entirely eliminate the segrega-

bility of the disks, and although search was hindered by these manipulations, the hindrance did not raise the slopes of the best fit lines to levels typically found in earlier studies of color/shape conjunctions. The steepest slopes, found for the right/left orientation condition, were 8.6 and 18.2 msec/item for target-present and target-absent trials, respectively; typical slopes lie in the ranges 12–25 and 25–50 msec/item, respectively (Pashler, 1987; Treisman & Gelade, 1980; Treisman et al., 1977). A final manipulation verified that search for color/shape conjunctions is substantially hindered by the complete elimination of segregability.

The items were red and blue-green disks of size and chromatic properties identical to those in earlier experiments. However, the disks were not smoothly shaded; rather, bright and dark regions were separated abruptly at an edge. The half-fields of these red and blue-green disks were either 1.30 or 0.70 times as luminous as the white background, thus providing a contrast of 30%. These disks contained the same luminance polarities as did the corresponding shaded disks but were not segregable, as noted by Ramachandran (1988a, 1988b).

Mean reaction times from this experiment, in which the red target and blue-green distractor disks had bright top halves and the red distractors had bright bottom halves, are shown in Figure 4 (target-present, open; target-absent, filled). The slope of the best fit line to the target-present reaction times is 20.7 msec/item [$F(1,10) = 84.1, p \leq .00005$] and that of the best fit line to the target-absent reaction times is 46.9 msec/item [$F(1,10) = 152$,

Figure 3. Means of the observers' reaction times for 20%, 10%, and 5% contrast conditions with shaded disks, plotted as a function of the number of items in the display. Results from target-present trials are indicated by the open symbols. Circles mark the mean reaction times in the search for a red disk of 20% contrast, brightest at the top, among blue-green disks brightest at the top and red disks brightest at the bottom with the same contrast: search is parallel. Squares and triangles refer to search in similar experiments with disks at 10% and 5% contrast, respectively. Search is hindered by reducing contrast sufficiently. Percent correct rates in the 20%, 10%, and 5% contrast conditions were identical, 94. See text for discussion.

$p \leq .00005$]. The slopes of the lines are within the range considered normal for color/shape conjunctions; a comparison of Figure 4 and Figures 2 and 3 shows that search is substantially hindered by the complete elimination of segregability.

Adaptive Color Detection Within Figures

In a final experiment, we examined whether adaptive mechanisms of color detection, described by us earlier (D'Zmura, 1991), can operate solely within figures determined by mechanisms of segregation. The key to showing that detection is adaptive is to demonstrate that a target of some fixed color is sought by using mechanisms with chromatic properties that vary in a way that optimizes detectability in any one task. As in the earlier work, we used an orange disk as a target and examined its detectability when presented among (A) red and blue-green, (B) yellow and blue, (C) yellow-green and violet, and (D) red and yellow distractor disks. The CIE 1931 (x, y) chromaticities of these disks are shown in Figure 5.

Each of the four chromatic conditions that involved search for the orange disk was presented within a putative figure provided by mechanisms of segregation. The disks with colors listed in the four conditions above were shaded to appear convex (brightest at the top, with luminance contrast 90%); an equal number of orange concave distractor disks provided a background. The four conditions, combining color and shading information, are shown schematically in the color circles on the left of Figure 6; "+" and "-" signs indicate convexity and concavity, respectively.

We expected, in Condition A, that observers would be able to use a spatially extended detection mechanism tuned

Figure 4. Means of the observers' reaction times for an experiment with bipartite disks, plotted as a function of the number of items in the display. Open circles mark the mean reaction times from target-present trials for the search for a red disk, bright at the top, among blue-green disks bright at the top and red disks bright at the bottom; filled circles mark the reaction times from target-absent trials. Search is "serial." The percent correct rate was 97. See text for discussion.

Figure 5. The CIE 1931 (x, y) chromaticities of red (R), orange (O), yellow (Y), yellow-green (YG), blue-green (BG), blue (B), and violet (V) disks. The neutral background (W) was of luminance 25.5 cd/m^2 and had chromaticity (.275, .290).

to yellow events to detect the orange target among red and blue-green distractors and that this yellow-sensitive mechanism would operate only on items within the figure comprising convex disks: search should be parallel. Likewise, in Condition B, we expected a parallel search to be conducted by a detection mechanism sensitive to red events within the figure comprising convex disks, and in Condition C, by a mechanism sensitive to orange events. Finally, in Condition D, we expected search to be serial and self-terminating, reflecting the absence of a spatially extended, chromatically narrow-band mechanism sensitive to orange and insensitive to both red and yellow (D'Zmura, 1991).

The results for the three observers are shown in the rightmost three columns of Figure 6. The results of only one observer (M.D.) are perfectly consistent with the expectations: (1) reaction times in Conditions A, B, and C did not depend on the number of distractors, and (2) reaction times increased with number of items in Condition D in a way consistent with an explanation based on serial, self-terminating search. The results from Observers P.L. and C.T., while similar to those from M.D., departed mildly from the expectations. Their results show a small dependence of reaction time on number of distractors in Conditions A, B, and C. The slopes of the best fit lines to the target-present reaction times of P.L. in Conditions A, B, and C were 6.5, 4.2, and 4.2 msec/item, respectively; those for C.T.'s observations in the same conditions were 8.5, 10.1, and 7.5 msec/item. Although these slopes are shallower than typical slopes found in search for color/shape conjunctions (12–25 msec; see above), they reflect a mildly greater difficulty with Conditions A, B, and C for Observers P.L. and C.T. All observers, finally, found search in Condition D substantially more difficult than in Conditions A, B, and C, as expected.

Taken as a whole, the results of this final experiment support the notion that observers can apply chromatically optimal detection mechanisms to segregated representations of visual information.

Figure 6. Results of search for an orange, convex (+) disk among orange concave (-) distractors and (A) red and blue-green convex distractors, (B) yellow and blue convex distractors, (C) yellow-green and violet convex distractors, and (D) red and yellow convex distractors. These conditions are represented in the schematic color circles in the first column; the half-filled circle refers to the color of the orange convex (+) target and the orange concave (-) distractors; the filled circles refer to the colors of the convex (+) distractors. Results for Observers M.D., P.L., and C.T. are shown in the second, third, and fourth columns, respectively. Average reaction times (in milliseconds) from an experimental run are plotted for each observer as a function of number of items (1, 8, 16, 32) in the display. Slopes of the best fit lines to the target-present and the target-absent reaction times in milliseconds/item for Observers M.D., P.L., and C.T., respectively, were as follows: (A) 2.3, 1.8; 6.5, 25.2; and 8.5, 14.4. (B) 1.0, 1.9; 4.2, 16.0; and 10.1, 15.9. (C) 1.0, 1.5; 4.2, 10.2; and 7.5, 17.9. (D) 11.2, 22.2; 23.8, 62.5; and 35.7, 58.6. Percent correct rates in Conditions A, B, C, and D for Observers M.D., P.L., and C.T., respectively, were (A) 96, 98, and 92; (B) 95, 99, and 90; (C) 99, 98, and 95; (D) 95, 96, and 96.

DISCUSSION

We use a clear case of parallel search for a conjunction of color and shape to show that color detection mechanisms operate on segregated representations of the visual field.

Prior work on search for color/shape conjunctions has generally shown that these are sought serially (Carter, 1982; Egeth, Virzi, & Garbart, 1984; Green & Anderson, 1956; Quinlan & Humphreys, 1987; Treisman & Gelade, 1980; Treisman et al., 1977), although more recent work has stressed speeded search through limited forms of parallelism (Mordkoff, Yantis, & Egeth, 1990; Pashler, 1987; Wolfe, Cave, & Franzel, 1989). The most salient difference between the colored disks that we used and the shapes used in earlier experiments in which observers searched serially for color/shape conjunctions (e.g., letters or numbers) is that the present shapes are segregable when colored.

Nakayama and Silverman (1986a, 1986b) first identified cases of parallel search for conjunctions that suggested the importance of segregation. They reported parallel search for color/stereo, stereo/motion, and color/motion conjunctions. In each case, one of the features helped observers segregate items that were interspersed spatially into figure and ground, while the other feature helped observers identify the target from among the items within the figure. Further results on parallel search for conjunctions include those of Steinman for stereo/Vernier offset conjunctions and those of McLeod and colleagues for conjunctions of shape and motion (McLeod, Driver, & Crisp, 1988; Steinman, 1987). Their results are again consistent with the notion that search is conducted within figures determined by mechanisms of segregation (Treisman & Sato, 1990).

In color-based search, items of color identical to that of the target do not hinder search if they lie sufficiently far away from the target and if the observer confines his or her attention to the neighborhood of the target. A superficially similar but nontrivial observation was made by Treisman, who suggested early on that observers can restrict color-based search to a figure segregated from other items by the grouping principle of proximity (Treisman, 1982).

The present results show that observers sought targets defined by conjunctions of color and shape completely in parallel. The experiments show that parallel search is possible without the benefit of segregation according to item color, which has been shown to increase the speed of search for color-shape conjunctions (Bundesen & Pedersen, 1983; Carter, 1982; Egeth et al., 1984; Farmer & Taylor, 1980; Green & Anderson, 1956; Smith, 1962). Were color used to segregate a display, the slope of the function that relates reaction time to the number of displayed items would decrease with reduction in the number of distractors with colors similar to that of the target. Yet in our first set of experiments, trials with 1, 8, 16, and 32 displayed items always had 0 or 1, 3 or 4, 7 or 8, and

15 or 16 distractors sharing the color of the target, respectively. Thus, the shallow slopes are not due to few same-colored distractors and consequent color segregability.

We cannot be absolutely certain that parallel search is undertaken within a segmented representation of the display in our experiments, even though the manipulations of shading orientation, contrast, and pattern brought about clear changes in the segregability of the disks and concomitant degradations in performance. Direct manipulations of shading invariably involve a change in the light distribution in the image that feeds mechanisms of segregation, and it is conceivable, although highly unlikely, that the search is undertaken directly in a domain of two-dimensional features.

With this caveat, the results of the last experiment show that a model comprising adaptive mechanisms of color signal detection, developed through work on simpler displays (D'Zmura, 1991), may be extended to more complex displays by supposing that the mechanisms can operate on figural chromatic information within a segmented representation. Items like the red concave disks in the first experiment are simply not presented to the mechanism that detects the red convex disk in a spatially parallel way, despite the identity of their colors. By far the most parsimonious, if qualitative, explanation for this egregious nonlinearity places chromatic detection mechanisms beyond the basic perceptual mechanisms of segregation.

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