Asymmetries in Simple Feature Searches for Color

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Observers were required to search for and find a target stimulus that differed from distractor stimuli only in chromaticity. Pairs of target and distractor colors were chosen so that in some conditions the two members of a pair differed in hue, in saturation, or in both hue and saturation. For each type of condition, a number of pairs of colors representing varying degrees of perceptual difference were chosen. Each member of each pair of colors served as both the target and distractor color while the other member of the pair served in the remaining role. The largest asymmetries in search times occurred when the target and distractors differed in saturation. Somewhat smaller asymmetries occurred with differences in both saturation and hue, and no asymmetries occurred with hue differences. Results suggest that the asymmetries are related to the time required to encode and transmit the chromatic information centrally rather than the properties of the search process itself. Copyright © 1996 Elsevier Science Ltd.

Visual search   Color

INTRODUCTION

Simple feature searches for target stimuli that differ from distractor stimuli on a single relevant perceptual dimension are characterized by two prominent phenomena (Treisman & Souther, 1985). Under some conditions the time required to find the target stimulus, here referred to as the search time, is independent of the number of distractor stimuli present in the display, while under other conditions the search time increases with the number of distractors present. The first result will be referred to as "pop-out", while the second result will be referred to as "extended search". Pop-out usually occurs for stimuli that are easily discriminable while extended searches occur when target and distractors are perceptually similar (Treisman & Souther, 1985; Treisman & Gormican, 1988; Nagy & Sanchez, 1990; Nagy et al., 1990). The second phenomenon occurs when the roles of target and distractor stimuli are reversed. Under some conditions the reversal has no effect on the search time while under other conditions it does affect the search time (Treisman & Gormican, 1988; Williams & Julesz, 1990; Ivry & Cohen, 1992; Cohen, 1993). For example, Treisman and Gormican (1988) found that the mean time required to find a magenta target stimulus among blue distractor stimuli was shorter than the mean time required to find a

target of the same blue among distractors of the same magenta. When the reversal affects the search time, an asymmetry is said to occur.

Treisman and Gormican (1988) suggest that three types of stimulus conditions result in such asymmetries. First, searching for the absence of a feature that is present in the distractors is slower than searching for the presence of a feature that is not present in the distractors. Second, searching for less of a feature defined on a quantitative dimension is slower than searching for more of that feature. Third, searching for prototypical features is slower than searching for features that are non-prototypical. Treisman and Gormican (1988) regard both the pop-out phenomenon and the asymmetries as evidence for a feature analysis model of visual search in which responses to stimuli are pooled within feature maps and attention is used to vary the number of stimuli included in the response pool.

Since the coding of color within the initial stages of the visual system is relatively well understood, it is an ideal stimulus domain for exploring search asymmetries. Evidence suggests that color is coded within two different neural channels early in the optic nerve and the lateral geniculate nucleus (see Lennie & D'Zmura, 1988). The signal or response in one of these channels, which we will call the LM channel, is related to the difference in the excitations of the long and middle wavelength cones (L–M). The signal in the other channel, which we will call the S channel, is related to the difference in the excitation of the short wavelength cones and the sum of the excitations in the long and middle

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wavelength cones (S-[L + M]). Chromatic signals in these two chromatic channels appear to be independent of each other (Krauskopf et al., 1982; Lennie & D'Zmura, 1988). However, signals in these two channels do not correspond exactly to the red–green and blue–yellow perceptual axes defined by psychophysical experiments using hue cancellation (Hurvich & Jameson, 1956) and color-naming methods (Boynton et al., 1964). Presumably the responses in these channels are subjected to further processing in the cortex.

Krauskopf et al. (1986) and D'Zmura (1991) have suggested that the two channels may recombine to produce many higher order mechanisms in the cortex, each tuned to a narrow range of hues that might encompass intermediate hues such as orange or purple. On the other hand, DeValois and DeValois (1993) proposed recently a model in which the responses of the LM and S channels are summed together in two different ways in the cortex to produce the red–green and blue–yellow neural representations that correspond to the perceptual axes. DeValois and DeValois (1993) regard the physiological evidence for such a stage as inconclusive, but they propose also a fourth stage, corresponding to color-selective complex cells in the cortex, which is constructed by summing inputs from the third stage. The fourth stage is composed of four types of cells, each of which responds to only one perceptual hue category, either red, green, yellow or blue, but gives no response to the other hues.

The fourth stage of DeValois and DeValois (1993) corresponds closely to the feature maps hypothesized by Treisman and Gormican (1988) in their feature analysis model of visual search. The feature maps each code the presence of one particular hue, either redness, greenness, blueness or yellowness, as a function of location in the visual field. The magnitude of the response at each location in the map would indicate the degree or strength of the hue at that location. Below we will use the term feature map to refer to a high-level coding stage of the sort envisioned by Treisman and Gormican (1988) without making specific assumptions about the number or tuning of these maps. We will reserve the term channel for the two peripheral mechanisms (LM and S) which have been described in the optic nerve and lateral geniculate nucleus.

The color channels in the peripheral visual system are defined well enough so that it is possible to choose physical stimuli that excite a channel to a particular degree or do not excite it at all. Thus it is possible to choose color stimuli so as to produce in the peripheral chromatic channels each of the three types of conditions resulting in asymmetries described by Treisman and Gormican (1988). The purpose of this study was to investigate each type of asymmetry as a function of the color difference between the target and distractor stimuli, in order to determine the relationships among pop-out, extended search and asymmetries. We wished also to investigate the magnitude of the asymmetries as a function of color difference. According to the feature

analysis model proposed by Treisman and Gormican (1988), the magnitude of the asymmetry should decrease with increasing color difference between the target and distractors, and asymmetries should not occur for stimuli that produce pop-out.

METHODS

Subjects

Four observers, two males and two females, participated in the study. They ranged in age from 20 to 30 years. Three of the observers were paid students. The fourth observer was one of the authors (SC). All had normal or corrected-to-normal visual acuity as measured with a Snellen chart and normal color vision on the Ishihara Pseudoisochromatic Plates. All had some experience with the experimental task prior to participating in the experiments described here.

Apparatus

The stimuli were generated on a Barco (CDCT 5151) color monitor. Displays were generated with an AED 767 graphics processing unit, which was driven by an Apple IIE computer. The monitor was calibrated with a Minolta chromameter (CS 100). The calibration data were used to generate look-up tables giving phosphor luminance levels for each of the available 256 phosphor levels. The look-up tables were used in conjunction with a program written in Apple basic to generate the phosphor levels required to produce a desired color. A least-squares procedure was used to determine the nearest approximation to the desired color. Phosphor levels for desired colors were then stored in files which were used by another program that generated the displays and ran the experiments. The experimental program also collected response times and provided feedback to the observer. Responses were collected from a joystick controller. A button on the joystick was used to indicate that the target had been found and the joystick control was used to indicate the location of the target.

The stimuli were circular disks 0.125 deg in diameter. The disks were presented on a dark surround in random locations within a circular area 4 deg in diameter, centered on the monitor screen. The minimum spacing between the disks was set so that no two disks overlapped in the display. The luminance of the disks was held fixed at 15 cd/m² throughout all of the experiments. On each trial, 54 disks were presented. The disks were identical except for the target disk, which differed from the other 53 in chromaticity. The target and distractor chromaticities are described for each experiment below.

Procedure

Procedures were similar for all experiments except for the stimulus colors used. On each trial, the stimulus presentation was preceded by a brief warning tone and a fixation cross presented in the center of the display area. After a variable interval of 0.25–2 sec, the fixation cross was turned off and the stimulus array including both the

target and distractors appeared. The variable interval was used to prevent anticipatory responses. The subject's task was to locate the disk that differed in color from the other disks as rapidly as possible. The observer depressed a button on the joystick control after the target had been found. The display was terminated by the response and a cursor appeared on the monitor. The observer then placed the cursor at the target location and again depressed the response button. The target and cursor then were presented together briefly to give feedback about the correct target location. Tones were used also to give feedback. The trial was counted as correct if the cursor had been placed within 0.5 deg of the center of the target disk. Observers had no difficulty placing the cursor within the criterion distance when the target had been correctly located. During the next 6–12 sec, the next trial was generated and the next trial sequence began.

Trials were run in blocks of ten. Within each block, the target and distractor colors were held constant. Typically, 14 blocks of 10 trials were run within a 1 hr session. The target and distractor colors were varied across blocks. The order of the blocks was randomized within each session. Throughout the experiments, only response times for correct trials were collected. Though speed was emphasized, accuracy was maintained at a high level. If two errors were made within a block of 10 trials, the observer was required to repeat that block. This ensured that the accuracy rate was 90% or better. The display was viewed in a darkened room from a distance of 2 m. Observers typically participated in one, or occasionally two, 1 hr sessions on a given day. Each condition in each experiment was completed by each observer on four different days. All four observers had fairly extensive experience with the experimental task in pilot experiments prior to the collection of the data reported here. Thus, all four should be regarded as highly practised observers.

EXPERIMENT 1

In the first experiment, we investigated the asymmetry for prototypical and non-prototypical stimuli. Treisman and Gormican (1988) found that search times for prototypical target stimuli among non-prototypical distractors were longer than search times for non-prototypical targets among prototypical distractors. Color stimuli were used in one of their experiments. The authors suggest that the non-prototype targets resulted in faster searches because they produced activity in a feature map not stimulated by the prototype distractors. Prototype targets excited a feature map also stimulated by non-prototypical distractors and were more difficult to detect, because of the pooling of responses within a feature map. Treisman and Gormican (1988, p. 31) predicted that if the difference between prototypical and non-prototypical stimuli were made large enough, the asymmetry would disappear and pop-out would occur for both.

We tested this prediction by pairing unique hue stimuli with several hues at varying distances from the unique
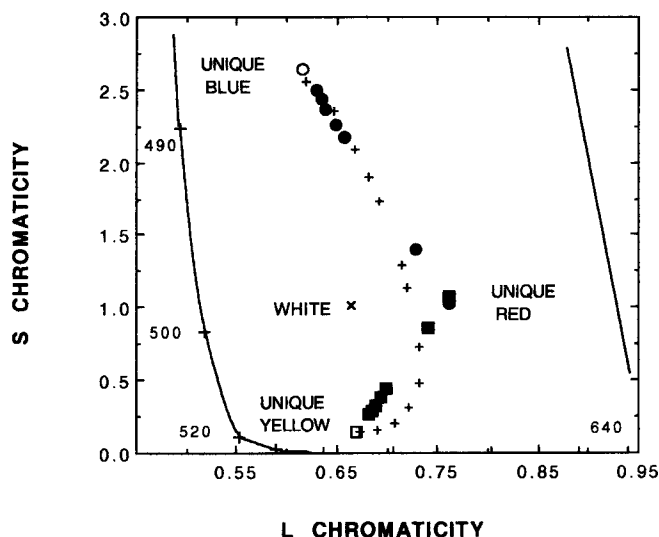

FIGURE 1. Chromaticities of the stimuli used in Experiment 1 are shown in the cone excitation diagram. Small plus signs indicate Munsell hues of constant chroma or perceived saturation.

hue in color space. The locations of unique red, unique yellow and unique blue in the color space were determined for each observer with a staircase procedure. Unique blue and unique yellow were chosen as prototypes. Seven chromaticities were selected as non-prototypes from each of two lines connecting unique blue and unique yellow with unique red. Each of these chromaticities was paired with the prototype hue anchoring one end of the line (either unique blue or unique yellow). The chromaticities chosen for one subject are shown in the cone excitation diagram (MacLeod & Boynton, 1979) in Fig. 1. The unique, or prototype, hues are shown as open symbols while the non-prototype hues are shown as solid symbols. The small plus signs in the figure indicate the loci of different hues of constant chromatic saturation from the Munsell book of color (Chroma = 8). The points have been drawn in to show that the chromaticities selected were all similar in perceived saturation and differed primarily in hue.

The chromatic saturation was approximately constant for stimuli along each line because the excitation level in the S channel was decreased as the excitation level in the LM channel was increased. Thus, the information in these two channels and the feature maps associated with them is redundant. An observer presumably could use either channel to locate the target. Unique blue and unique yellow each served both as the target and distractor chromaticity while the other seven chromaticities paired with the unique hue served in the remaining role to give a total of 28 conditions.

Results

Results for pairs containing unique blue are shown in Fig. 2(A) while those pairs containing unique yellow are shown in Fig. 2(B). The L chromaticity difference
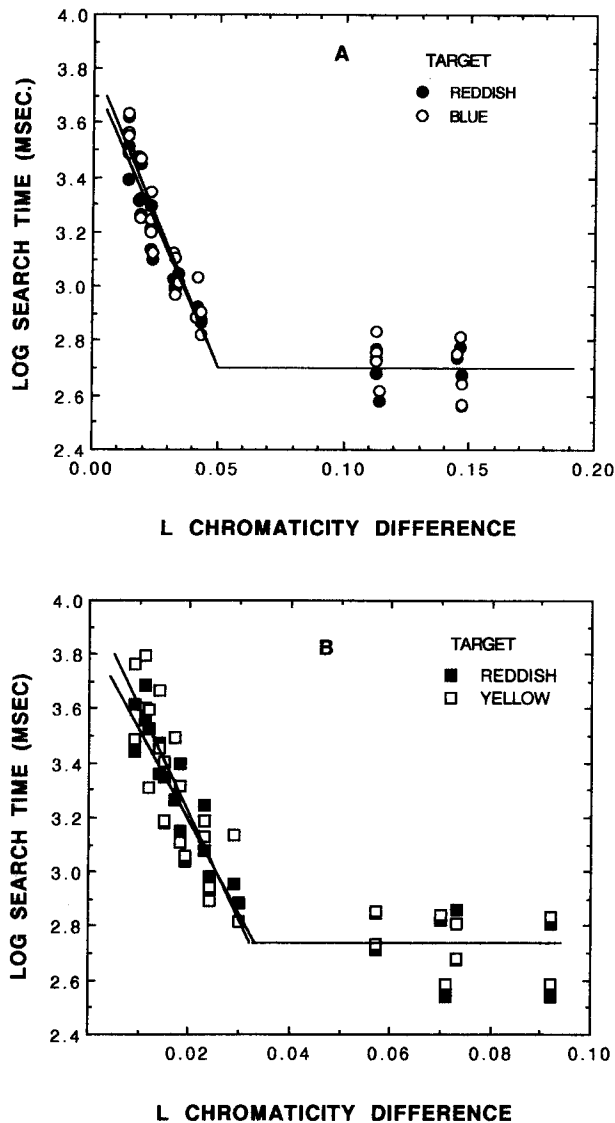
FIGURE 2. Mean log search times plotted against the chromaticity difference for the pairs of stimuli used in Experiment 1. Results for the blue–red set of colors are shown in (A) and results for the yellow–red set are shown in (B).

between the target and distractor stimuli is plotted along the abscissa. Note that the log of the search time (in msec) is plotted on the ordinate. Open symbols in each figure indicate that the prototype was the target and the non-prototype was the distractor. Solid symbols indicate the reverse. Each data point indicates the mean log search time for one observer taken across 40 trials. Since results from the four observers were similar, they have been combined in the figure.

Clearly, the log search time decreases with increasing color difference between the target and distractors up to a point in both figures. For the two largest color differences on the right in each panel of the figure, search times are quite fast, indicating that pop-out occurred (see Nagy & Sanchez, 1990). This was tested in a brief experiment in which the number of distractor stimuli was varied from 6

to 54. Results confirmed that the search time did not vary with the number of distractors for the two largest color differences in each panel of Fig. 2. The other notable feature of the results is that the prototype target and non-prototype target conditions are similar, regardless of the color difference between the target and distractors. The mean difference in log search times for prototype and non-prototype targets was 0.033 (SEM = 0.011) for the unique blue set and 0.037 (SEM = 0.020) for unique yellow set with searches for the non-prototype faster in both cases.

Separate three-factor ANOVAs (target type × color difference × repetition) were run on the data from each figure. The data were further subdivided by performing separate analyses on data for the five smallest color differences, which produced extended searches, and the two largest color differences, which produced pop-out. Since only four subjects participated in the experiments, there is reason to be concerned that the low d.f. would produce unstable error term estimates and low power statistical tests. Therefore, error terms for all main effects (subject × target type, subject × color difference and subject × repetition) were pooled to produce a single error term using the methods described by Dunn and Clark (1987). This error term was then used to test all main effects. A similar procedure was used to test two-way interactions; all available error terms were pooled.

For the unique blue data in Fig. 2(A), the ANOVA showed that the main effect of color difference was significant $(F(4,24) = 66.38, P < 0.001)$ for the five smallest color differences. No other main effects or interactions were significant. In particular, no main effect for target type was found $(F(1,24) = 1.65, P > 0.05)$, and no interaction between target type and color difference was found $(F(4,57) = 0.2183, P > 0.05)$. The ANOVA on the two largest color differences showed no significant main effects or interactions.

The analysis of the unique yellow data in Fig. 2(B) also showed that the main effect of color difference was significant for the five smallest color differences $(F(4,24) = 36.2, P < 0.001)$. The main effect of target type was again not significant $(F(1,24) = 1.82, P > 0.05)$, but the interaction of target type by color difference was significant $(F(4,57) = 2.89, P < 0.05)$. All other main effects and interactions were not significant. Further analyses revealed that only the smallest color difference yielded a significant difference for target type $(F(1,12) = 7.16, P < 0.025)$ and that the non-prototype targets did produce shorter search times in this condition. The analysis of the two largest color differences again revealed no significant effects.

The negatively sloped straight lines in the figures were fit to the data with linear regressions. The horizontal lines were drawn through the mean of the log search times for the two largest color differences. The intersection of the two lines in each figure was taken as an estimate of the color difference required to achieve pop-out. We have referred to this point as the critical color difference (Nagy & Sanchez, 1990, 1992). This procedure was used to
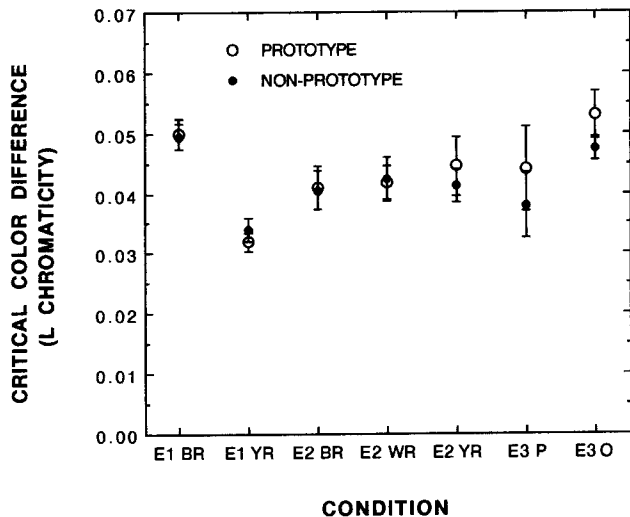
FIGURE 3. Mean critical color differences for each set of colors used in the three experiments. Error bars indicate 95% confidence intervals based on 16 estimates.
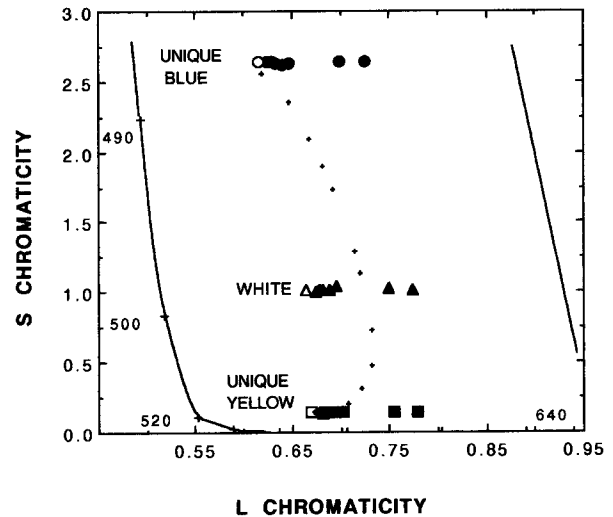

FIGURE 4. Chromaticities of the stimuli used in Experiment 2 are shown in the cone excitation diagram. Small plus signs again indicate Munsell hues of constant chroma or perceived saturation.

calculate critical color differences for each subject, target type and repetition, resulting in 16 estimates of the CCD for each target type in each panel of the figure. The overall means of these 16 estimates are shown in Fig. 3 (labeled E1BR and E1YR), with error bars indicating 95% confidence intervals. The color difference required to achieve pop-out does not appear to depend on target type, as the previous analysis of variance would suggest, but it does differ for the yellow and blue stimuli.

The results of this experiment suggest little difference in search times for prototypical and non-prototypical targets and no evidence for an asymmetry which varies in magnitude with color difference. Thus our results disagree with those reported by Treisman and Gormican (1988) and provide little evidence for their prediction that the size of the asymmetry should be dependent on the magnitude of the perceptual difference between the target and distractors. The difference in results is discussed further below.

EXPERIMENT 2

The second experiment was designed to test the hypothesis that search times for the absence of a feature are longer than search times for the presence of a feature. Unique blue, unique yellow and white were chosen as anchor stimuli and each was paired with seven reddish stimuli selected from horizontal lines extending toward the reddish portion of the cone excitation diagram (see Fig. 4). The small crosses in Fig. 4 again indicate the loci of different hues of approximately constant perceived saturation. The stimuli along the blue–red and yellow–red lines differ from each other in both perceived hue and saturation. The stimuli along the white–red line differ primarily in perceived saturation since they are all a similar reddish hue. Each member of each of these 21 pairs of stimuli served as the target and distractor

chromaticity while the other member of the pair filled the remaining role for a total of 42 conditions.

The blue, yellow and white stimuli were chosen to produce little or no excitation in the LM channel or in a red feature map. They differ from each other in the amount of excitation produced in the S channel and in yellow and blue feature maps. The seven stimuli (paired with each anchor stimulus) were chosen so as to hold constant the level of excitation in the S channel, but differ from the anchor stimulus in that they produce some excitation in LM channel or the red feature map. If signals in the blue, yellow and red feature maps were independent of each other, the signals in the yellow and blue feature maps should be irrelevant to the task. Target and distractor stimuli should be discriminable only on the basis of activity in the red feature map, and results for these three sets of stimuli should be similar.

For the conditions in which the reddish stimulus was the target, the feature analysis model (Treisman & Gormican, 1988) predicts that the presence of activity in the red feature map should be detected rapidly because the distractors produce little or no activity in the red feature map. For the conditions in which the blue, yellow or white stimuli serve as the target, searches should be slower since the observer must search for the absence of activity in a red feature map stimulated by the distractors.

Results

Results for the blue–red, yellow–red and white–red sets of colors are shown in Fig. 5(A, B & C), respectively. Again, the L chromaticity difference is plotted along the abscissa and the log search time (in msec) is plotted on the ordinate. Again, open symbols indicate that the unique hue stimulus (blue, yellow or white) was the target among reddish distractors and solid symbols indicate that the reddish stimulus was the target among
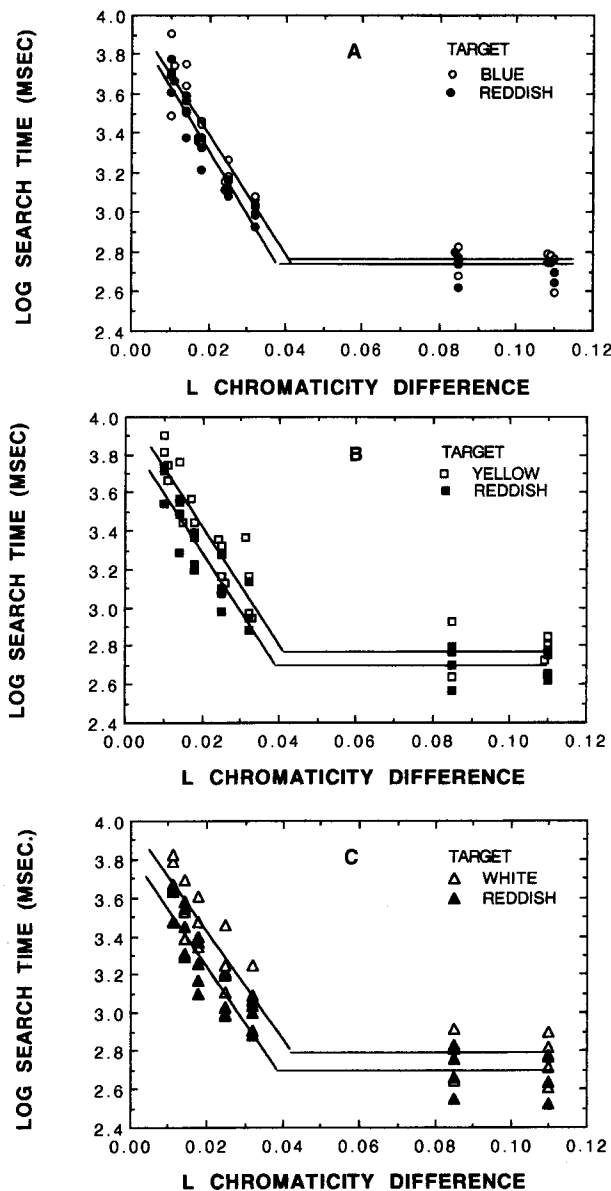
FIGURE 5. Mean log search times plotted against the chromaticity difference for pairs of stimuli used in Experiment 2. Results for the blue–red set of colors are shown in (A), those for the yellow–red set are shown in (B), and those for the white–red set are shown in (C).

unique hue distractors. As in the first experiment, search time decreases with increasing color difference up to a point in each figure and the two largest color differences in each panel produce pop-out. Search times for the unique hue, or feature-absent, targets are generally longer than those for the reddish, or feature-present, targets regardless of the color difference. The asymmetry is largest in (C), somewhat smaller in (B) and smallest in (A).

Four-way repeated measures ANOVAs (target type × color difference × color set × repetition) were performed on the combined data from the four observers. As in the first experiment, separate analyses were performed on the five smallest color differences and the two largest color

differences and pooled error terms were used for calculations of the F ratio. The analysis of the five smallest color differences showed a significant main effect for color difference as in Experiment 1 $(F(4,36) = 196.85, P < 0.001)$. However, the analysis also revealed a significant main effect of target type $(F(1,36) = 28.18, P < 0.001)$ and a significant interaction between target type and color set $(F(2,140) = 10.75, P < 0.01)$, suggesting that asymmetries occurred but varied in size across color sets. All other main effects and interactions were not significant. Further analysis showed that the effect of target type was significant for all three color sets, but the mean difference between the feature-absent and the feature-present conditions was largest for the white–red set $(0.17, SEM = 0.015)$, slightly smaller for the yellow–red set $(0.13, SEM = 0.018)$ and smallest for the blue–red set $(0.07, SEM = 0.017)$.

Analysis of the two largest color differences from each set of colors suggested that main effect of color difference was not significant, confirming that the color differences were large enough to produce pop-out. The main effect of target type was again significant $(F(1,18) = 21.34, P < 0.001)$ and the interaction of target type and color set was again significant $(F(2,50) = 3.95, P < 0.05)$, suggesting that asymmetries occurred, but again varied in size across color sets. Further analysis showed that the asymmetry was significant for the white–red and yellow–red sets, but not for the blue–red set. The mean difference between feature-absent and feature-present conditions again was largest for the white–red set $(0.08, SEM = 0.008)$, slightly smaller for the yellow–white set $(0.06, SEM = 0.026)$ and smallest for the blue–red set $(0.03, SEM = 0.016)$. Note that these asymmetries are all smaller than the corresponding asymmetries for smaller color differences that produce extended searches.

The straight lines in Fig. 5 were again fit to the five smallest color differences with linear regressions and horizontal lines were drawn through the mean log search times for the two largest color differences as in Experiment 1. The critical color differences, defined by the intersections of the two lines, are similar for all three color sets and both target types. Critical color differences for these conditions are shown in Fig. 3 (labeled E2BR, E2WR and E2YR). The asymmetry appears to have little effect on the color difference required to achieve pop-out.

EXPERIMENT 3

The final experiment was designed to test the hypothesis that more of a feature shared by target and distractors can be found more rapidly than less of that feature. The stimuli were selected from lines extending from near-white to orange and purple. The selected chromaticities are shown in Fig. 6. The most saturated stimulus on each line (solid symbol) was paired with each of the other seven less saturated stimuli (open symbols) on the line. Again, each member of each pair of chromaticities served as both target and distractor in different conditions while the other member of the pair
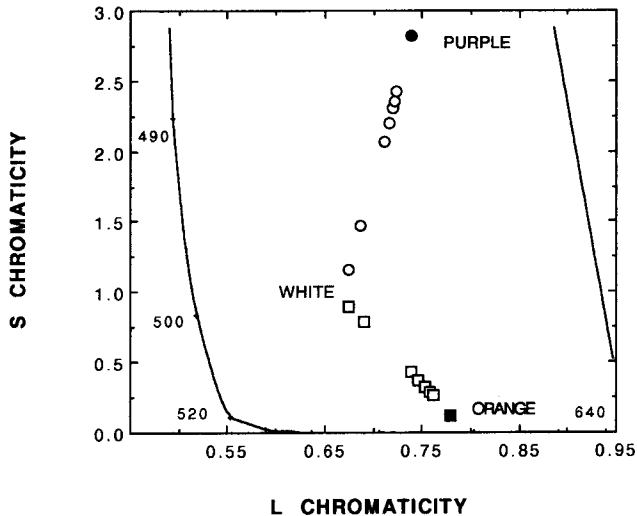
FIGURE 6. Chromaticities of the stimuli used in Experiment 3 are shown in the cone excitation diagram.

served in the other role. Thus the 14 pairs of chromaticities give a total of 28 conditions. The stimuli along each line were similar in hue, but differed primarily in saturation. The yellow and red feature maps provide redundant information about the target and distractor stimuli from the orange line, and the blue and red feature maps provide redundant information about target and distractor stimuli from the purple line. In each condition, the target and distractors differ in the strength of the excitation they produce in both of the relevant feature maps. Presumably an observer could search either or both feature maps for targets. According to the feature analysis model, faster searches should occur when the more saturated stimulus serves as the target. The asymmetry should become smaller as the saturation difference between the target and distractors becomes larger, and the asymmetry should not occur for differences that produce pop-out.

Results

Results for the orange and purple stimuli are shown in Fig. 7(A & B), respectively. Log search times (in msec) are again plotted against the L chromaticity difference between the target and distractors, with solid symbols indicating that the more saturated member of each pair of chromaticities served as the target and open symbols, indicating that the less saturated member served as the target. In both panels, log search times again decrease regularly with increasing saturation difference between target and distractors up to a point. Both figures show clear evidence of an asymmetry with desaturated targets, resulting in slower searches than saturated targets. The asymmetry appears to be present for all of the color differences tested including the two largest differences in each figure, which produce pop-out.

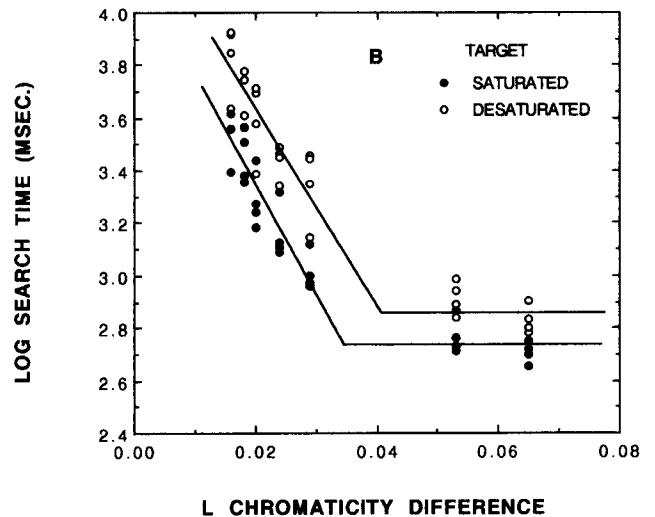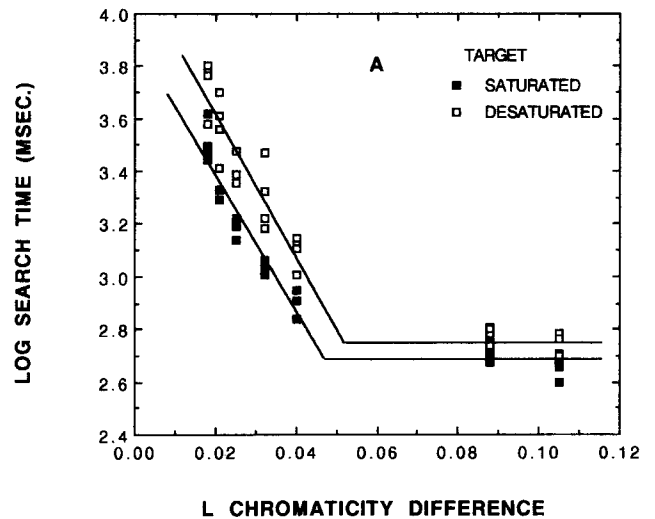The data from the orange and purple sets were analyzed in separate three-way ANOVAs (target type ×

FIGURE 7. Mean log search times plotted against the chromaticity difference for pairs of stimuli used in Experiment 3. Results for the orange set of colors are shown in (A) and those for the purple set are shown in (B).

color difference × repetition). Again, search times for the five smallest color differences and the two largest color differences were analyzed separately. For the five smallest color differences from the orange set, the analysis showed significant main effects of target type $(F(1,24) = 78.95, P < 0.001)$, color difference $(F(4,24) = 71.82, P < 0.001)$ and repetition $(F(3,24) = 4.53, P < 0.025)$. All three main effects were also significant for the five smallest color differences from the purple condition [target type, $(F(1,24) = 223.26, P < 0.001)$; color difference, $(F(4,24) = 83.80, P < 0.001)$; repetition, $(F(3,24) = 4.55, P < 0.025]$. All interactions for both the purple and orange color sets were not significant. Notably, the interaction between target type and color difference was not significant for either color set [orange, $(F(4,57) = 0.18, P > 0.05)$; purple, $(F(4,57) = 0.60, P > 0.05]$. The mean difference in log search times for saturated and

desaturated targets was 0.22 (SEM = 0.021) for the orange set and 0.30 (SEM = 0.020) for the purple set.

Analysis of the two largest color differences from the orange set gave a significant main effect of target type ($F(1,15) = 12.72, P < 0.01$), but all other main effects and interactions were not significant. For the purple set, the analysis of the two largest color differences showed significant main effects of target type ($F(1,15) = 43.69$, $P < 0.001$) and color difference ($F(1,15) = 12.38$, $P < 0.01$). All other main effects and interactions were not significant. The mean difference in log search times for saturated and desaturated targets was 0.07 (SEM = 0.013) for the orange conditions and 0.13 (SEM = 0.014) for the purple conditions. Thus, the asymmetry was again somewhat smaller for the two largest color differences than for the five smallest color differences as in Experiment 2.

Critical color differences were calculated with the same methods used in the first two experiments. These are shown on the right-hand side of Fig. 3 (labeled E3P and E3O). Again, the asymmetry does not appear to have much effect on the size of the critical color difference, but the critical color differences do appear to be somewhat smaller for the purple set than for the orange set of colors.

DISCUSSION

Several aspects of the results are inconsistent with an explanation based on the feature analysis model. Below, we discuss the results from each of the three experiments in relation to the predictions of this model and then discuss an alternative explanation of search asymmetries.

The first experiment was designed to investigate the asymmetry for prototype and non-prototype targets. According to the feature analysis model (Treisman & Gormican, 1988), non-prototypical distractors that are similar in hue to a prototypical target should make a prototypical target difficult to find because they produce a high level of activity in the feature map for the prototype. With larger hue differences, the excitation of the prototype feature map by the distractors should decrease and the time required to find the prototype should decrease. Searches for non-prototype targets should be faster than those for prototypes with small hue differences, and the size of the asymmetry should decrease with increasing hue difference. Treisman and Gormican (1988) found evidence for such an asymmetry with three pairs of colors (red–magenta, blue–turquoise and yellow–lime), but we note that the authors commented on the fact that the asymmetry was quite small. Converted to logarithmic units, the asymmetry was less than 0.05 log units for the largest display size used (12 items).

Experiment 1 produced little evidence of an asymmetry for 14 yellow–orange and blue–purple pairings of prototype and non-prototype colors, regardless of the size of the hue difference. The source of this difference in results is unclear. Our stimuli were chosen so that all of the stimuli were equal in luminance and similar in chromatic saturation, but Treisman and Gormican used reflective stimuli that were similar in lightness and

saturation. Our stimuli were chosen to represent a range of hue differences, while Treisman and Gormican (1988) used a single, rather large hue difference for each of their three color pairs. The small hue differences used in our study should result in even larger asymmetries according to the feature analysis model. The use of a larger display size (54 items) in the present study also would be expected to result in larger asymmetries. One major difference between the two studies is that observers had only to report the presence or absence of a target in the Treisman and Gormican study, while in this study a target was present on every trial and had to be located spatially. However, it is not clear why this procedural difference might result in the absence of an asymmetry in the present study. We conclude that both studies indicate that if an asymmetry does exist for prototype and non-prototype colors, it is very small (less than 0.05 log units) regardless of the magnitude of the hue difference between the pair of colors.

The second experiment was designed to test the asymmetry in searches for the presence vs the absence of a feature. According to the feature analysis model, an observer initially has access only to the pooled activity in a feature map. Thus the absence of activity at a particular location in a feature map activated at many other locations should be more difficult to detect than the presence of activity at that location in a feature map that is not being excited at other locations. All of the pairs of colors in Experiment 2 were chosen so that one member of the pair produced little or no activity in the red feature map while the other member of the pair excited the red feature map. The two members of each pair were chosen to excite the S channel to the same degree, so that target and distractor stimuli could not be discriminated on the basis of the activity in the S channel. If feature maps derived from the S and LM channels were independent of each other, then the excitation level in the S channel should be irrelevant to the task and the three sets of colors should produce similar results.

An asymmetry was present for all three sets of colors. However, the size of the asymmetry differed for the three sets, being largest for the white–red set and smallest for the blue–red set. Perhaps the simplest interpretation of this result is suggested by the model of DeValois and DeValois (1993). In their model, the S and LM channels are combined to form the red, yellow and blue feature maps in such a manner that excitation of the M cones contributes to the excitation of the blue feature map (Alpern et al., 1983; Drum, 1989). Thus, holding excitation in the S channel constant while varying the excitation of the LM channel would not hold constant the excitation level in the blue and yellow feature maps. If the search task is conducted at the level of these feature maps, then the activity in either map could be used to determine whether a target was present in a particular pool of stimuli. In a speeded task, the observer might choose the map which is more strongly excited. Since the blue and yellow feature maps are strongly excited in the blue–red and yellow–red conditions of Experiment 2,

these two maps might be used in searching for the targets that produce little activity in the red feature map, while the red feature map might be used to search for targets that more strongly excite it. This strategy would work to reduce the size of the asymmetry in these two conditions compared to the white–red condition in which the excitation of all feature maps would be low for targets that do not strongly excite the red feature map.

Another important feature of the results in Experiment 2 is that the size of the asymmetry on the logarithmic ordinate is to some extent independent of color difference within each color set. For color differences that are small enough to produce extended searches, the lack of a significant interaction between target type and color difference suggests that the size of the asymmetry in log units is nearly constant. In linear units, extended searches for white targets are consistently about 1.48 × longer (0.17 log units) than those for reddish targets, while searches for yellow and blue targets are 1.35 (0.13 log units) and 1.17 × longer (0.07 log units). In linear units of time, the size of the asymmetry does increase with decreasing color difference between the target and distractor stimuli in a very regular way. The ratio between the feature-present and feature-absent search times is constant. This result is consistent with the feature analysis model, which predicts that the asymmetry should become larger with smaller color differences.

Asymmetries are present also for color pairs that produce pop-out in the white–red and yellow–red sets. The feature analysis model does not predict asymmetries when the color difference is large enough to produce pop-out. The asymmetries are somewhat smaller than the asymmetries for color pairs that produced extended searches, a factor of 1.20 (0.08 log units) for the white–red set and a factor of 1.15 (0.06 log units) for the yellow–red set. The large color differences in the blue–red set did not produce a significant asymmetry, but the search times for feature-present targets were, again, on average slightly faster than those for feature-absent targets (mean difference of 0.03 log units or a factor of 1.07).

The colors selected for Experiment 3 were chosen so as to test for an asymmetry in searches for targets that differed from distractors in a quantitative manner. Target and distractor stimuli differed primarily in chromatic saturation. Asymmetries were present for both the orange and purple sets of colors used in this experiment. Again, the size of the asymmetry in logarithmic units was independent of the size of the saturation difference between target and distractors when the saturation difference was small enough to produce extended searches. Saturation differences that were large enough to produce pop-out also resulted in a significant, though somewhat smaller, asymmetry. This result is not consistent with the expectations based on the feature analysis model, which would predict that the asymmetry should be absent for differences large enough to produce pop-out.

The white–red color set from Experiment 2 might also have been included in Experiment 3, since the pairs of target and distractor colors used in that set differed primarily in chromatic saturation. These three sets of colors produced the largest asymmetries. Thus, the asymmetry was largest for the three conditions in which target and distractors differed in the strength of the chromatic signal. For color differences small enough to produce extended searches, the mean size of the asymmetry was 0.23 log units or a factor of about 1.70 for these three sets of colors. For color differences large enough to produce pop-out, the mean size of the asymmetry was 0.093 log units or a factor of 1.24 across the three sets.

Somewhat smaller asymmetries occurred for the blue–red and yellow–red color sets of Experiment 2. In these two color sets, the target and distractor stimuli differed from each other in both hue and chromatic saturation. The blue and yellow stimuli were less saturated than the reddish-blue and reddish-yellow stimuli they were paired with. For color differences that produced extended searches, the mean asymmetry was 0.10 log units (a factor of 1.26) and for color differences that produce pop-out it was 0.045 (a factor of 1.11). Thus, the presence of a hue difference, along with a saturation difference between target and distractors, reduced the size of the asymmetry. In Experiment 1, where target and distractor stimuli were similar in chromatic saturation but differed in hue, there was no asymmetry. Together, the results of the three experiments suggest that asymmetries result primarily from saturation differences between target and distractor. Searches for highly saturated targets are faster than searches for desaturated targets. Overall, the results do not agree well with the predictions of the feature analysis model and suggest an alternative explanation discussed below.

Search asymmetries may result from the time required to encode and accumulate information about saturated and desaturated stimuli rather than the properties of the search process. Gast and Burns (1979), Nissen (1977) and Nissen et al. (1979) found that duration thresholds, simple reaction times and discriminative reaction times were longer for detecting single desaturated stimuli than for detecting single saturated chromatic stimuli. Nissen et al. (1979) argued that highly saturated stimuli generate stronger neural responses that can be encoded and conducted to cortical centers in a shorter time than desaturated stimuli. Nissen (1977) (see also McGill, 1963; Luce & Green, 1972) reviewed the extensive literature on the inverse relationship between stimulus intensity and reaction time. Much of this literature suggests that the rate at which information is conducted centrally to the cortex increases with increased stimulus intensity. Thus, response times are shorter for intense stimuli, at least in part, because the required information reaches the cortex more rapidly. Nissen et al. (1979) argued that a similar principle holds for chromatic signals. Highly saturated chromatic stimuli generate stronger signals in the peripheral stages of the visual system that are conducted to the cortex at a more rapid

rate than weak signals. Thus, the information required to make a response accumulates more rapidly in cortical centers and reaction times are shorter for highly saturated stimuli than for desaturated stimuli.

Results in the three search experiments described here suggest that significant asymmetries in search times also occur only when target and distractors differ in chromatic saturation. Search times are shorter for saturated targets than for desaturated targets. In general, this asymmetry occurred regardless of the size of the color difference between targets and distractors or whether pop-out or extended searches occurred. This pattern of results suggests that the asymmetry may be due to the rate at which information is accumulated in the cortex rather than the properties of the search process in these cortical centers. This would explain why the asymmetry occurred with both large and small differences between target and distractors. In either case, it would take longer to accumulate the information needed for a response when the target stimulus is desaturated.

The explanation offered above can also explain why the size of the asymmetry is roughly constant in logarithmic units for extended searches. Suppose, as do Treisman and Gormican (1988), that the observer examines smaller and smaller pools of stimuli as the target and distractors are made more similar and the task becomes more difficult. Then the mean search time becomes longer as the color difference is made smaller because, on average, a larger number of small pools must be examined successively. The examination of each pool takes some time, because the observer must accumulate enough information to determine reliably whether or not the pool contains the target stimulus. When the target is saturated, this interval may be relatively short because the rate of accumulation of information is high for the saturated target. When the target is desaturated, the examination of each pool takes longer because the rate of information accumulation is slower for the desaturated target. Also, suppose that the difference in the times required to search pools for the saturated and desaturated targets is approximately constant and that the time required to search a pool is independent of the size of the pool. The size of the saturation difference between the target and distractors affects only the number of stimuli included in each pool examined. Then the difference in mean log search times for saturated and desaturated targets will be constant, even though the mean log search times become longer as the saturation difference is made smaller.

When the hue of a stimulus is changed but its chromatic saturation is held constant, the strength of the signal in one of the peripheral chromatic channels decreases but the strength of the signal in the other chromatic channel increases. In the search task the information in either chromatic channel could be used to discriminate the target and distractor stimuli. If the task is speeded as in the experiments described above, the observer could use the information from the channel in which it accumulates most rapidly. When the hue

difference between target and distractors is small, the observer's decision could be based on the channel or feature map which is most strongly stimulated by both target and distractors. Because the hue difference is small, both target and distractor stimuli produce responses that are similar in strength in this channel or feature map, and the rate of accumulation of information would be similar for both stimuli. Thus, there would be little change in the search time when the roles of target and distractor are reversed. When the hue difference between the target and distractors is great, the target hue will produce a strong response in one channel while the distractor hue will produce a strong response in the other channel. Thus the observer can always search the channel in which the response is strong and the rate of accumulation of information is high. Again, reversing the roles of target and distractors should produce little effect on the search time.

The explanation given above also can account for differences in the blue–red, yellow–red and white–red sets in Experiment 2. If the signals in the yellow and blue feature maps are not independent of signals in the red feature map (DeValois & DeValois, 1993), altering the excitation level of the red feature map also will alter the excitation level in the yellow and blue feature maps. Since there is a fairly high excitation level in the yellow and blue feature maps in the yellow–red and blue–red conditions, the strong signals in these channels can be used with fairly short pool examination times and searches for the yellow and blue targets will not be much longer than searches for the reddish targets. In the white–red condition, the excitation level of the yellow and blue feature maps is near zero and alterations in this level caused by changes in the excitation of the red feature map will still result in a weak signal that will require a long pool examination time and result in a larger asymmetry.

In summary, several aspects of our results are inconsistent with the feature analysis model of simple feature searches (Treisman & Gormican, 1988). Asymmetries occur only with stimulus pairings consisting of stimuli that elicit strong and weak responses in the relevant chromatic channels and feature maps. This result suggests an alternative explanation of the asymmetries that attributes them to the time required to accumulate information about strong and weak stimuli, rather than to properties of the search process itself.

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