Chromatic and luminance signals in visual memory

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The efficiency of chromatic and luminance signals was studied in a set of tasks requiring the discrimination of two colors. Discrimination was measured around an adapting achromatic light and a number of other points in a three-dimensional color space. As a baseline, discrimination thresholds were measured under conditions permitting a side-by-side comparison of stimuli in space or time. For the spatiotemporal configurations used in these experiments, chromatic signals were more efficient than luminance signals in terms of the difference in cone excitation required at the discrimination threshold. When stimuli were separated in both space and time, so that memory was required for their comparison, the efficiency of luminance signals was attenuated further, while chromatic signals retained their efficiency. Further experiments showed that the addition of a memory requirement did not impair the accuracy of luminance discrimination when the two test colors could be placed in distinct perceptual categories with respect to the surround color. Our results indicate that chromatic signals are particularly efficient in simple color discrimination tasks requiring even the barest amount of memory, especially when the perceptual categorization scheme is not available for the comparison of stimuli.

INTRODUCTION

The present study was motivated by a desire to identify and analyze simple visual tasks in which chromatic information has a greater value to the observer than luminance information. Given published measurements of spatial and temporal contrast sensitivity functions,[1–5] it is easy to find stimulus conditions that favor one or the other type of information in either spatial or temporal discrimination. In real life, discrimination or identification of two stimuli can often not be done on the basis of side-by-side spatial or temporal comparisons, i.e., memory is often required when two colors are being compared. When the colors to be compared are separated in time, discrimination performance deteriorates.[6–8] In this study we show that chromatic information is of greater value to an observer than luminance information in the class of tasks requiring memory.

Evidence that chromatic signals are more efficient than luminance signals in some color comparison tasks dates as far back as Maxwell's[9] observation that the standard error of the chromatic component of a color match was smaller than that of the luminance component. Maxwell's experiment required the observer to discriminate between two contiguous bipartite fields under steady viewing conditions. More recently the issue of chromatic versus luminance efficiency has received renewed attention for a variety of visual tasks.[10–26] In this study we explore two main issues: (1) the effect of the addition of a memory requirement on discrimination tasks, in particular, differences in the capacities to remember chromatic and luminance components, and (2) the contribution of perceptual categories to discrimination when colors have to be compared by memory. In the experiments described here we compared discrimination thresholds when spatial and temporal parameters of tests were varied. Differences in performance as a function of these parameters could be due not only to memory requirements but also to changes in the temporal frequency spectrum, contrast-response range limitations in color mechanisms, and changes in adaptation state. In the comparisons that we made, we controlled for these potential contaminants to isolate the effects of memory requirements.

In experiment 1 we measured discrimination thresholds around a midwhite adapting light in a three-dimensional color space, employing tasks that permitted a side-by-side comparison of tests either in space or in time. In experiment 2 discrimination was measured around a number of other points in the color space, using the same tasks as in experiment 1, and thresholds were compared with those around the midwhite adapting color. This provided a baseline to quantify the response limitations of color mechanisms under the conditions employed. Given this baseline, discrimination was measured in experiment 3 around the same points with a task in which tests could not be compared on a side-by-side basis in space or in time, so that memory was required to perform the comparison. Discrimination performances were then compared for the task requiring memory and a task from experiment 2 that had the same temporal component but that did not have a memory load. In experiment 4 tests were separated by a time delay to determine whether the results of the previous experiment could have been due to visual persistence. In experiment 5 observers were adapted to the judgment point around which discrimination was measured to control for the influence of adaptation processes. In experiment 6 we examined the effects of the categorization of test colors with respect to the surround color.

EXPERIMENT 1. DISCRIMINATION THRESHOLDS AROUND THE ADAPTING WHITE FOR TESTS SEPARATED IN SPACE OR TIME: EFFICIENCY OF LUMINANCE AND CHROMATIC SIGNALS

The first experiment was used to establish sensitivity baselines under steady-state adaptation. One of the roles of adaptation appears to be the adjustment of the operat-

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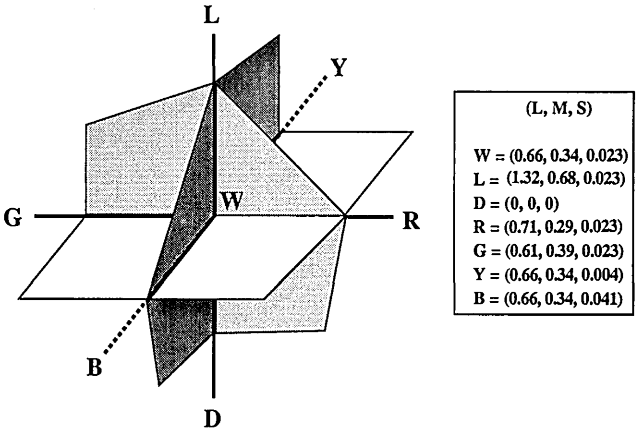


Fig. 1. Three-dimensional cardinal color space within which colors were defined. The *RG*/*YB* equiluminant plane is shown in white. The *RG*/*LD* plane is shown in light gray, and the *YB*/*LD* plane is shown in dark gray. Color discrimination was measured around judgment points distributed in the three planes shown. The boundaries of the planes indicate the range of colors possible with the equipment used. The maximum values attainable on the axes are given as (L, M, S) excitations in MacLeod–Boynton coordinates.[31] Midwhite (W) is at 50 cd/m^2.

ing range to give maximum discriminability around the adapting point.[27,28] In this experiment we compared the efficiencies of chromatic and luminance signals under these optimum conditions.

Discrimination thresholds along the three cardinal directions defined below were measured around the adapting white light by using tests separated either in space or in time but not both: tests were presented either simultaneously and adjacent to each other or sequentially (with no intervening temporal gap) at the same retinal location. The tasks did not require memory since the observer merely had to detect a change from one test to the next across either a spatial or a temporal border.

Color Specification

Lights were specified in a three-dimensional cardinal color space, shown schematically in Fig. 1.[29,30] This space has properties suited to the experiments described here. First, cone excitations vary linearly along straight lines in this space. The thresholds for the discrimination of two colors can thus easily be given in terms of the difference of cone excitations required for discrimination. In addition, equiluminant chromatic signals and luminance signals are clearly defined in terms of cone excitations. Also, by adapting to the midwhite color at the center of the space, we find that a systematic exploration of discrimination around points distributed evenly around midwhite is straightforward. The limits of the axes are given as (L, M, S) excitations in MacLeod–Boynton chromaticity coordinates,[31] where L, M, and S refer to excitations of the long-, the middle-, and the short-wavelength-sensitive cones, respectively. The center of the space, W, is an achromatic light with a luminance equal to 50 cd/m^2. The limits of the three planes shown indicate the range of colors that could be generated with the equipment used, i.e., the perimeters of the planes show the maximum deviations from midwhite (W) attainable in a particular direction. The cardinal axes are defined in terms of changes in cone excitation. Along the *LD* axis, all three cone inputs are varied in equal proportions. The total cone excitation (L + M + S) is used as a metric. Along the *RG* axis, the excitations of the L and the M cones are traded off against each other while the sum of excitation is kept constant. The difference between the L- and the M-cone inputs (L − M) serves as a metric is this case. The *YB* axis is defined by changes in the S-cone input only, so that S-cone excitation serves as a metric.

Equipment

Stimuli were displayed on a Tektronix 690SR television monitor running at a frame rate of 120 Hz, interlaced. The 512 × 480 pixel display subtended 10.67° × 10° of visual angle. The display was driven by an Adage 3000 frame buffer generator that permitted 10-bit specification of the intensity of each gun. To ensure linearity, the output of each of the three TV cathode guns was corrected with a backtransform via a look-up table. For details of calibration and color specification, see Zaidi and Halevy.[32] The equipment described here was used for all the experiments in this study.

Task

To measure color discrimination, we chose two colors from a given color axis so that W lay midway between them, and their separation in color space was varied while W was maintained as their center. Discrimination thresholds were measured by using a two-alternative forced-choice task against a standard. *Three* tests were presented; the middle test in a sequence was the standard and was the same color as one of the other two. When the three tests were separated in space, observers had to say whether the left- or the right-hand sector was different from the standard. For stimuli separated in time, observers had to say whether the first or the third interval was different. Observers responded by pressing buttons. Trials measuring discrimination along the three cardinal directions were interleaved randomly. Interleaved double-random staircases tracked the 79% correct point. Each data point is the mean of 12 transitions. The thresholds for tests separated in space and for tests separated in time were measured on the same day.

Observers

All the results shown are for one observer, one of the authors (WLS), who was emmetropic, tested color normal on the Farnsworth–Munsell 100-hue test, and had extensive experience with psychophysical experiments. Critical results were replicated with a second color-normal observer.

Spatial and Temporal Configurations of Stimuli

The steady adapting background color of 50 cd/m^2 was metameric to W in Fig. 1 in all the experiments in this study. Observers fixated a dark spot with a diameter of 1.2 arcmin at the center of a 10.67° × 10° uniform background field. The distribution of two test colors in three test intervals is described above in the Task subsection. The stimuli were three equal sectors of a circle with a 3° diameter that was centered on the screen. For tests separated in space (Fig. 2a), the three sectors of the circle were presented simultaneously for 0.5 s. The dotted lines in the schematics are for graphic exposition and were not present on the screen. The diagrams are not to scale. Presentation of the test was preceded by three cueing tones, and the end of the trial was signaled by a single

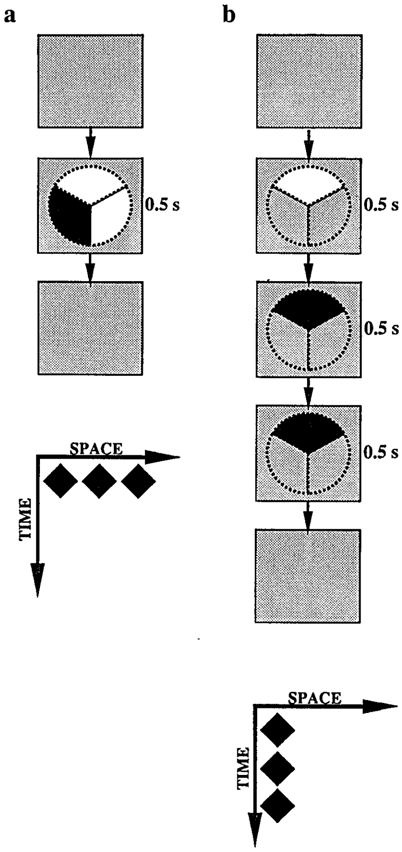


Fig. 2. Stimuli employed in experiments 1 and 2. The 10.67° × 10° uniform-background field was maintained at a steady adapting color of 50 cd/m^2, which was metameric to W. a, Tests separated in space: three equal sectors of a circle with a 3° diameter were presented simultaneously for 0.5 s. A fixation spot was located at the center of the circle. The figures are not drawn to scale, and the dotted lines were not present in the actual stimulus. The middle sector was the same color as one of the other two sectors, and observers had to say which sector was different from the other two. The spatiotemporal configuration is also shown schematically in the space–time diagram at the bottom. b, Tests separated in time: the middle sector was presented repeatedly, first taking on one test color and then changing to the next. The color of the middle interval was the same as that of one of the other two, and observers had to say whether the first or the third interval was different from the other two. The fixation spot was located on the lower apex of the sector.

tone. After the observer's response, there was a 1-s interval before the next trial. Other than during test presentations, the screen was uniform throughout the experiment. All three tests separated in time (Fig. 2b) were presented sequentially in the middle sector of the circle, i.e., the middle sector took on one test color and then changed to the next color. The fixation spot was located on the lower apex of the middle sector. Tones were used to demarcate the three test intervals in the following fashion. Three cueing tones signaled the beginning of the trial, and tests were presented for 0.5 s each. A tone sounded for the duration of the second test and was turned off at the onset of the third test. A short tone signaled the end of the trial; the screen was uniform thereafter. The change from one test color to the next occurred during the flyback period so that no blank interval was visible between tests. After an observer's response, there was a 1-s interval before the next trial.

We chose the relatively long presentation time of 0.5 s so that luminance signals were not favored in the baseline conditions.[2,4] In addition, long presentation times were required for chromatic stimuli to keep some thresholds from exceeding the limits of the color range available on the equipment.

In both conditions, each test stimulus could be discriminated from the reference color only by comparison across the one border (spatial or temporal) that it shared with the reference stimulus. When tests were presented simultaneously as sectors of a circle, the left- and the right-hand fields always differed across the 6 o'clock boundary, so that this border did not provide information as to which sector was different from the middle reference sector.

Results

The changes in cone excitations required to achieve discrimination thresholds around W are shown in Fig. 3 for tests varying along each of the three color lines. The relevant comparison is between the two experimental conditions within each panel. Thresholds are shown as the difference in cone excitation along a given cardinal axis. This difference can also be thought of as the distance between two points along a color line in Fig. 1. The direction along which tests differed is shown to the right of each panel. For these spatial configurations and presentation times, the thresholds were similar, irrespective of whether tests were separated in space or in time. The

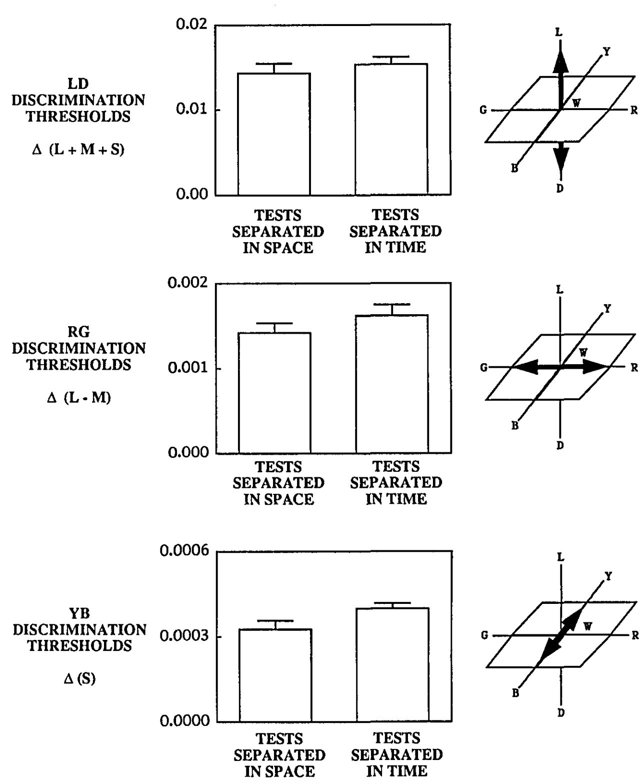


Fig. 3. Results from experiment 1: changes in cone excitation required to achieve discrimination thresholds around W for tests along three color lines. Thresholds are compared for tests separated in space and for tests separated in time. The error bars show the standard error of the 12 staircase transition values measured for a given threshold. The schematics of the color space to the right of the graphs show the directions along which the tests differed.

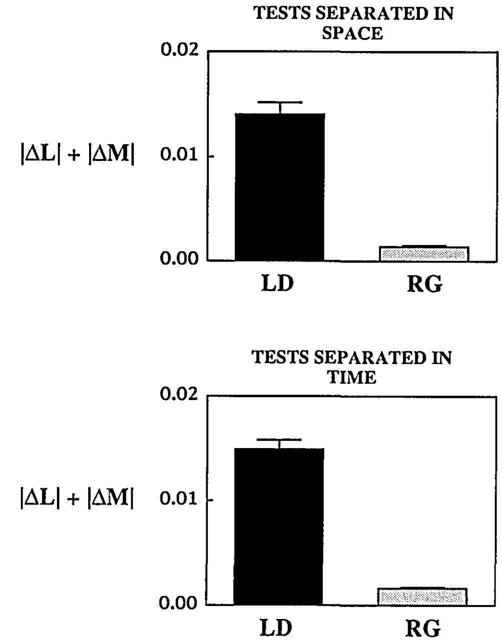


Fig. 4. Results from experiment 1: absolute change in L-cone signals plus absolute change in M-cone signals required for the *LD* and the *RG* thresholds around W.

error bars represent one standard error of the mean of the 12 transition values measured for a given threshold.

Because the color space in Fig. 1 is affine, like all spaces derived from color matches,[33] the thresholds along different color lines cannot be directly compared with each other. To compare thresholds for the *LD* and the *RG* tests, we considered only the L- and the M-cone contributions to the *LD* signal. Figure 4 shows the absolute changes in L-cone signals plus the absolute changes in M-cone signals required for *LD* and *RG* thresholds. Both for tests separated in space and for tests separated in time, *LD* thresholds were approximately nine times higher than *RG* thresholds. Adding S-cone contributions could only make relative threshold values for *LD* signals even larger.

The tasks described here could be performed by detecting changes across a spatial or a temporal border. The results show that luminance boundaries were less detectable than *RG* boundaries for relatively large stimuli (2.4 deg^2 for one sector) presented for relatively long intervals (0.5 s) when thresholds were defined in terms of the change in L- and M-cone inputs.

Some of the results given below are shown in terms of threshold elevations from the baseline data in Fig. 3. It should be remembered that the *RG* chromatic signal was more efficient than the luminance signal for baseline discrimination around W and that any further relative increase in efficiency for the *RG* signal was over and above this advantage.

EXPERIMENT 2. DISCRIMINATION AROUND COLORS REMOVED FROM THE ADAPTING POINT (W): COMPARISON FOR TESTS SEPARATED IN SPACE OR IN TIME

In a visual scene an observer often has to discriminate between two similar lights that are both different from the adaptation color. Sensitivity to such differences can be limited owing to response limitations in color mechanisms.[27,28,34-36] In this study we were interested not only in memory for colors near the adaptation point but also in discrimination around other colors. To this end we measured discrimination thresholds around points distributed throughout the color space, using the same two spatiotemporal stimulus configurations as in the previous experiment. In this way we characterized the effects of the contrast-response limitations under the particular conditions tested. Furthermore, some shifts in adaptation state were expected during the course of a single trial since tests were presented for 0.5 s each; previous studies have shown that luminance adaptation may shift considerably within 0.2 s.[37] This experiment thus served as a baseline to control for the effects of adaptation and response limitations. In the next experiment, experiment 3, we used a task requiring memory to discriminate between colors around the same points in color space as were used in this experiment. The differences in discrimination sensitivity between tasks could then be more easily ascribed to the introduction of the memory requirement, since adaptation and response limitations were already accounted for.

Discrimination around W represents a special case, since it allows one to place the test colors into two distinct perceptual categories. Since test colors were points chosen symmetrically around W in the color space, a change from one test to the other also represented a categorical change of the test colors with respect to the color of the surround, which remained at W throughout the experiment. For example, when tests differed in luminance, one test was lighter than the surround while the other was darker. On the other hand, for discrimination around a color that was, say, darker than the adapting W, both tests were also darker than the surround. Categorization of tests with respect to the surround color may help in discrimination, an issue that was explored in depth in experiment 6.

Judgment Points and Test Directions

We measured the discrimination thresholds for colors distributed within the three planes in the color space shown in Fig. 1. The discrimination thresholds were measured around a number of judgment points in color space. At every judgment point, discrimination was measured for test differing along each of the three cardinal directions. All judgment points and test directions employed in the experiments are shown in Fig. 5. The planes are shaded to correspond to the planes in Fig. 1: white for the equiluminant *RG/YB* plane, light gray for the *LD/RG* plane, and dark gray for the *LD/YB* plane. The arrows are centered on the judgment points and indicate the color line along which the tests differed from each other. ×'s indicate that arrows go through the plane of the paper. For ease of description, we refer to judgment points on the axes by the label for that half of the axis. For example, the judgment point on the *LD* axis that is lighter than W is called L. Judgment points were located halfway between W and the maximum value attainable on an axis in a given direction. In a procedure similar to that of experiment 1, a test metameric to the judgment point was not actually presented; instead, two colors that were equidistant from the judgment point along a given color line

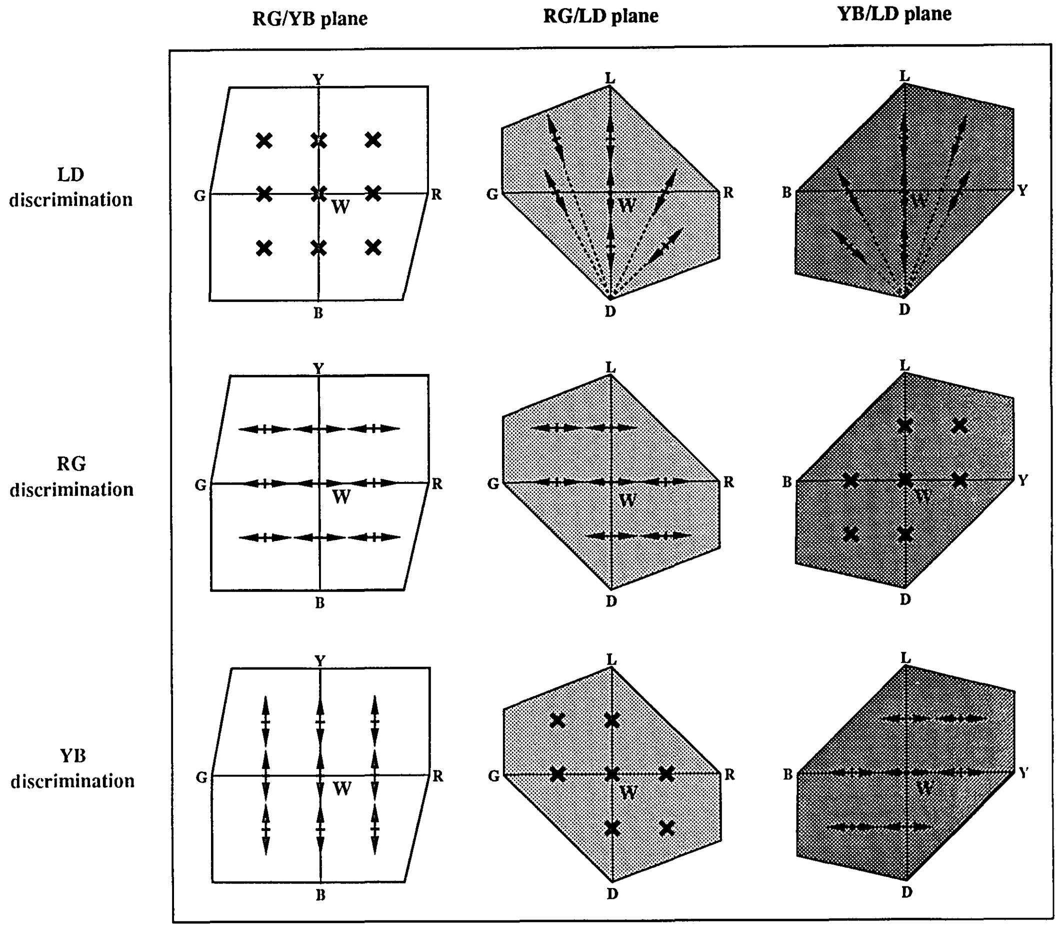


Fig. 5. All the judgment points and test directions employed in the experiments. The planes are shaded to correspond to the planes in Fig. 1. Test colors differed along the color lines indicated by the arrows. ×'s indicate that arrows go through the plane of the paper. Two colors were placed symmetrically around a judgment point, and their separation was varied to permit discrimination thresholds to be measured. Different test directions around any given judgment point are shown in separate panels.

were chosen, and their separation in color space was varied to measure the discrimination thresholds around that point. The *RG* and the *YB* test directions were parallel to the *RG* and the *YB* cardinal directions, respectively. For points on the *RG* axis, a *RG* change represents a change in saturation. An *RG* change across any point on the *YB* axis, including W, represents a change in hue. For judgment points not on the cardinal axes, an *RG* change represents a change in both hue and saturation. A similar description holds for *YB* changes. *LD* tests vary along a line going through the dark point, so that L, M, and S are varied proportionately in the same direction.

Experimental Procedure

The experimental procedure was similar to that employed in experiment 1: discrimination thresholds were measured independently along three color lines around every judgment point. In any given experimental session, thresholds were measured around two complementary colors, i.e., judgment points that were equidistant from W along a straight line through W, and trials were interleaved randomly by using double-random staircases. Observers were adapted to W throughout the experiment. For a given set of judgment points, the threshold for tests separated in space and for tests separated in time were measured during separate sessions on the same day.

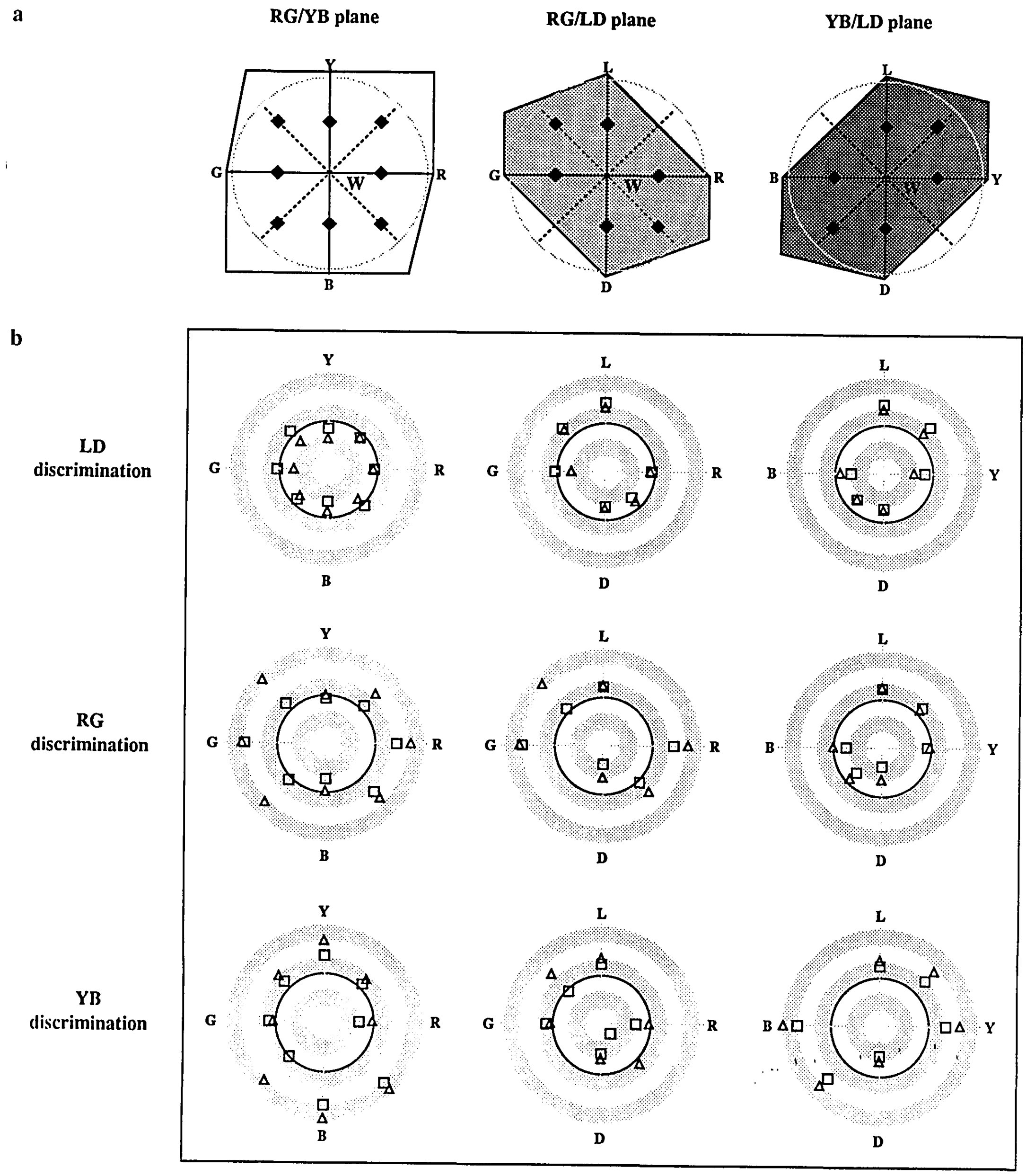
Results

In this experiment we were interested in the changes in discrimination thresholds that occurred when judgment points differed from the adapting color. To determine this change we compared the discrimination thresholds around a given judgment point with the corresponding thresholds around the adapting point W. An index of threshold change was calculated independently for the three color lines according to the following formula:

$$\log\left(\frac{\text{threshold around judgment point}}{\text{threshold around W}}\right). \tag{1}$$

Positive values indicate that the thresholds around a given judgment point and along a particular color line were elevated with respect to the comparable thresholds around W. Negative values indicate that the thresholds were lower around a given judgment point than around W, while a value of zero means that the thresholds were identical. To display the results for all judgment points within a color plane, we plot the log threshold change for a given judgment point along the radial line connecting that judgment point to W, as shown in Fig. 6a. Index values of zero are plotted on the dark circle, as shown in Fig. 6c. Positive values lie outside that circle, while negative values are plotted inside the circle. Concentric circles are spaced in steps of 0.3 log unit. Log threshold changes are shown as squares for tests separated in space and as triangles for tests separated in time.

The results for tests differing in luminance are shown in the top row of Fig. 6b. Discrimination around judgment points distributed in the equiluminant plane was similar to that around W; plot symbols therefore fall on or near the dark circle (left-hand panel). The middle and the right-hand panels in the top row of Fig. 6b show the results for judgment points on the planes spanned by the *LD* and the equiluminant chromatic axes. Log threshold changes are positive for judgment points above the central equiluminant plane and negative for judgment points be-



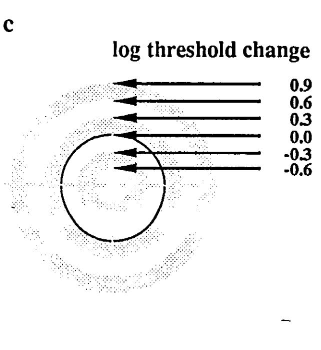


Fig. 6. Results from experiment 2: comparison of discrimination thresholds around judgment points distributed shown as diamonds in the three color planes in panel a to thresholds around the adapting color W. The log threshold change was calculated as the log of the ratio of the threshold around a given judgment point to the threshold around W [see formula (1)]. This was done for discrimination along each of the three color lines tested. a, The log threshold change is plotted along the radial line connecting a given judgment point to W. Index values of zero are plotted on the dark circle. Positive values lie outside the dark circle, while negative values lie inside. The magnitude of the index is represented by the distance from the dark circle. Concentric annuli are spaced in steps of 0.3 log unit. b, Results shown as squares for tests separated in space and as triangles for tests separated in time.

low the equiluminant plane. Thus *LD* thresholds were higher for judgment points lighter than the surround and lower for judgment points that had a lower luminance. Since each test was presented for 0.5 s, adaptation may have shifted an observer's sensitivity range toward these judgment points.[28,38,39] Thresholds would thus exhibit Weber's law behavior, being larger for higher luminances than for lower ones.

The results for discrimination along the *RG* line are shown in the middle row of Fig. 6b. The thresholds were elevated for judgment points displaced toward R or G in the equiluminant plane (left-hand panel). These results are comparable with those found in experiments measuring the detection of probes on a flashed background at points other than the adapting color.[35,36] Adaptation along the chromatic axes has a slower time course than adaptation along the luminance axis,[40–42] and the threshold elevations seen here probably reflect the limited response range of the *RG* cardinal mechanism. The *RG* thresholds did not change significantly for judgment points removed from W along the *YB* line. A similar independence of sensitivity for changes along one cardinal axis off points on another cardinal axis was found in experiments with briefly flashed fields.[35,36] The thresholds for discrimination along the *RG* line increased for judgment points lighter than the surround, while the thresholds decreased around judgment points that were darker than the surround. This pattern is similar to that seen for *LD* tests. Recent models of the properties of the cardinal mechanisms incorporate several independent sites at which adaptation can take place.[43] Measuring *RG* discrimination around judgment points whose luminance differed from the adapting luminance probably reflects the effects of the *RG* response range limitation together with the effect of preopponent change in adaptation to the new luminance level.

The results for discrimination along the *YB* line are shown in the bottom row of Fig. 6b. The overall pattern of threshold changes for different judgment points is similar to that of *RG* discrimination. Within the equiluminant plane, *YB* discrimination thresholds were elevated for judgment points displaced toward Y or B but not for judgment points displaced along the *RG* axis. Only S-cone excitation changes along the *YB* axis, while along the *RG* axis only the L- and the M-cone signals are varied. The independence of threshold elevations along these two directions indicates that, up to the level at which these thresholds are determined, S-cone signals probably interact little with an $(L - M)$ signal. The thresholds for judgment points lighter or darker than the surround were elevated or reduced, respectively, again showing the effects of preopponent adaptation processes (see Zaidi *et al.*[43] for a model consistent with these results). Although the experimental conditions differed, the results of the present experiments essentially replicate those of previous studies on response limitations and independence of cardinal mechanisms.[35,36,44,45]

For judgment points on the cardinal axes, the thresholds were generally quite similar for tests separated in time (triangles) or in space (squares), the largest difference being a factor of 2.3. Along the intermediate directions, though, the thresholds tended to be more elevated for tests separated in time than for tests presented simultaneously at different spatial locations. This is reflected in the plots by the fact that triangles are often positioned farther out than squares.

Our experiments also revealed a puzzling phenomenon for the discrimination task permitting a spatial comparison of stimuli. The discrimination thresholds along the chromatic cardinal axis on which a judgment point was located increased when the judgment point was removed from W along that axis; this has generally been ascribed to response limitations in the mechanism involved. Surprisingly, our results show that the thresholds were not elevated when judgment points were displaced along an intermediate chromatic axis. For example, *RG* discrimination thresholds around judgment point G were higher than *RG* thresholds around the judgment points in the adjacent intermediate directions, even though the only difference between the judgment points was the addition of a *YB* component (left-hand panel of middle row, Fig. 6b). In the graphs this is shown by the fact that squares along the intermediate directions are plotted nearer the dark circle than squares on the *RG* axis. This is evidence that the cardinal mechanisms do not function independently. Similar trends are found in the data of Krauskopf and Gegenfurter.[36] However, at present no model is available to account fully for these results.

In this experiment the difference between the efficiencies of chromatic and luminance signals decreased in some cases. For example, the luminance discrimination was the same around judgment point G (Fig. 6b, top left-hand panel) as it was around W, while *RG* thresholds increased by approximately a factor of 4 (left-hand panel of the middle row). Even in that case, the chromatic signal was still more efficient than the luminance signal by a factor of 2. One could possibly find judgment points at which the efficiencies of the chromatic and the luminance signals were the same simply by moving the judgment point even farther away from the adapting point. In these experiments, though, we were interested in establishing the baseline conditions for discrimination tasks involving side-by-side comparisons of tests across space or time at different points in color space. In experiment 3 we introduced a memory requirement for discrimination around the same set of judgment points.

Under the present experimental conditions, tests could be placed in distinct perceptual categories only for discrimination around W. The general loss of discrimination found for judgment points removed from W may partially reflect the fact that this categorization scheme was not available in those conditions. On the other hand, response limitation and adaptation processes probably featured prominently, since sensitivity for discrimination around D was actually higher than around W for all test directions. Adaptation and the ensuing Weber's law behavior thus overshadowed whatever sensitivity loss may have been due to the absence of the categorization scheme.

EXPERIMENT 3. COMPARISON OF A TASK REQUIRING MEMORY WITH A TASK PERMITTING A SIDE-BY-SIDE COMPARISON IN TIME

In experiment 2 stimuli could be discriminated on the basis of a spatial or temporal transition. In experiment 3 stimuli were separated simultaneously in space and in

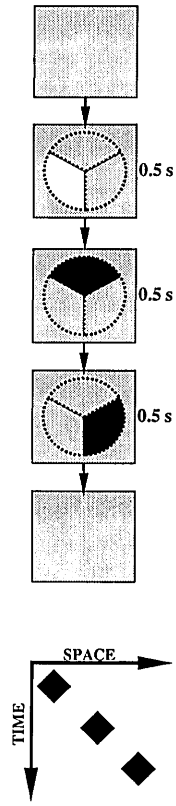


Fig. 7. Stimulus configuration used in experiment 3 for a color discrimination task requiring memory. Tests were separated in space and time: three equal sectors of a 3° circle were presented in a staggered fashion for 0.5 s each; the middle sector was the same color as one of the other two, and observers had to say which sector was different.

time, so that memory was required for a comparison of one test with another. The tests were presented sequentially at different locations, so that each retinal area was exposed to only one test, which precluded comparison across a temporal border, while the temporal staggering prevented a direct comparison of spatially adjacent tests. Since there was no added delay between the presentation of each of the staggered sectors and the next, this task required a minimal memory demand when two colors were being compared.

Since we were interested in the effects of the addition of a memory requirement on color discrimination, we compared the performance in the task requiring memory with the performance for stimuli separated in time measured in experiment 2, which served as a baseline task not requiring memory. The results of experiment 2 suggest a qualitative difference between spatial and temporal comparison tasks. Since a memory task always involves temporal separation we chose stimuli following each other in time but not requiring memory for the baseline condition. To attribute performance differences between tasks to the introduction of a memory load, we had to account for a number of other parameters. First, the results of the previous experiments served to form a baseline of thresholds at different judgment points. This controlled for changes in threshold that were due to response limitations and changes in adaptation state. Second, it seems unlikely that the performance differences between the memory task and the task permitting a side-by-side comparison of stimuli in time were due to the spatial difference in the stimulus configurations. Note that the task requiring memory in experiment 3 had the same spatial configuration as the one permitting a spatial comparison of stimuli from experiment 2. Third, the temporal components of the memory task were the same as for tests separated only in time. Finally, experiments 4 and 5 served as further controls for visual persistence and adaptation. Thus threshold changes found in this experiment can be attributed largely to the introduction of a memory requirement.

Spatial and Temporal Configuration of Stimuli

A schematic of the experimental conditions is shown in Fig. 7. The three sectors of the circle were presented in a staggered fashion for 0.5 s each. One sector was turned off and the next sector was turned on from one frame to the next, so that sectors were never presented simultaneously. After the observer's response, there was a 1-s interval before the next trial was begun. The beginning of a trial was cued by three tones, and the end was cued by a single tone.

Experimental Procedure

The procedure was the same as in the previous experiments. In any given session, the thresholds were measured around two complementary colors, and the trials were interleaved randomly. For a given set of judgment points, the thresholds for staggered sectors were measured on the same day as the thresholds for tests separated in time, which were described in experiment 2.

Results

The discrimination thresholds measured with staggered sectors were compared with the thresholds for stimuli separated only in time. We calculated an index reflecting the relative difference in thresholds between the two tasks according to the following formula:

$$\log\left(\frac{\text{threshold for staggered sectors}}{\text{threshold for tests separated in time}}\right). \tag{2}$$

This was done independently for tests along each of the three color lines. Positive values indicate that the thresholds for staggered sectors were higher than for tests separated only in time at a given judgment point, while negative values indicate that the thresholds were lower.

In Fig. 8 we show the results for discrimination around W and around judgment points on the cardinal axes. The abscissas represent the three cardinal axes, with letters indicating the judgment points lying on a given branch of an axis. In Fig. 8 we show only the results for discrimination along the color line on which a given judgment point was located, e.g., for points on the *LD* axis we show only the log threshold ratios for luminance discrimination. The schematics of the color planes to the right of the graphs show the corresponding judgment points and test directions.

The thresholds were similar for the two tasks for discrimination around W along each color line; the log threshold ratios at W therefore are close to zero in all three panels. Brightness discrimination performance around L or D (top panel of Fig. 8) differed for the two tasks: The

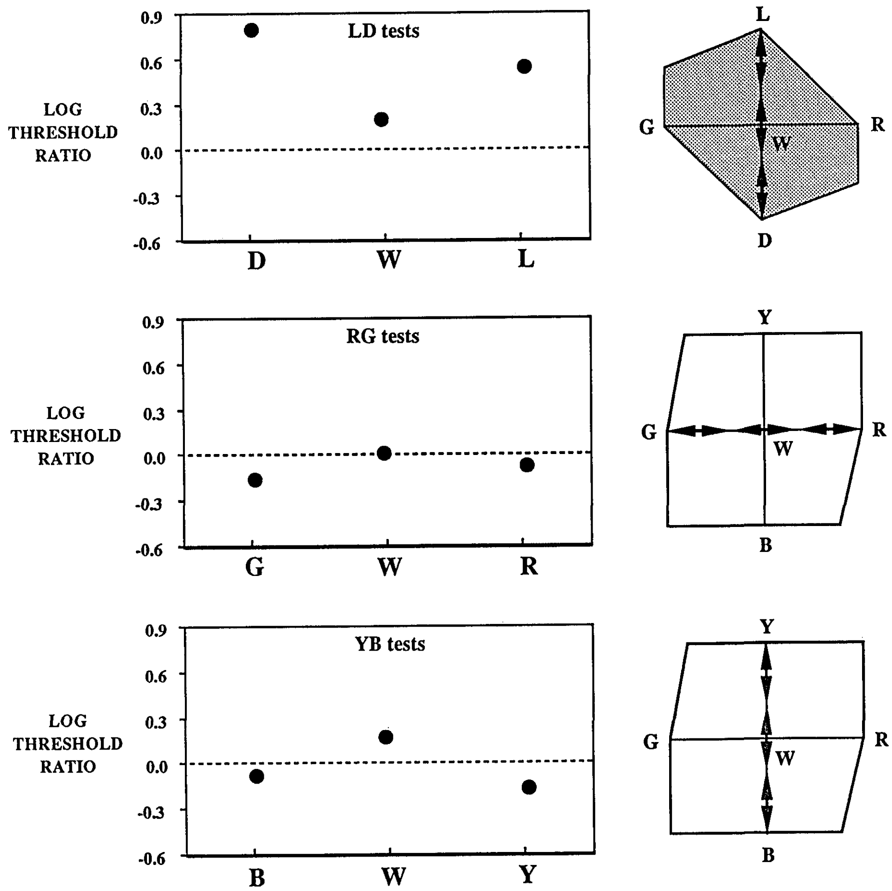


Fig. 8. Results from experiment 3: color discrimination performance with staggered sectors compared with performance with stimuli separated only in time. The log threshold ratio was calculated as the log of the ratio of the threshold for the memory task to the threshold for the tests separated in time [see formula (2)]. A value of zero indicates that the thresholds for the two test conditions were identical; positive values indicate that the thresholds were higher for the memory task. The panels show the results for discrimination around judgment points on each of the cardinal axes. Judgment points are identified by the letter corresponding to the branch of the cardinal axis on which they were located. The schematics of the color planes to the right of the graphs show the corresponding judgment points and test directions. The tests differed along the cardinal axis on which a given judgment point was located.

thresholds for staggered sectors were three to six times higher than for tests separated in time only. On the other hand, the thresholds were similar for the two tasks when saturation differences around judgment points on the chromatic axes were being discriminated (lower two panels). The log threshold ratios therefore are near zero for points R, G, Y, and B.

The full set of results, excluding the comparisons at W, is shown in Fig. 9b. The judgment points at which the comparisons for the two tasks were made are shown in Fig. 9a. The log threshold ratios are plotted as the distance along the radial lines on which the judgment points were located. Other specifications are as in Fig. 6.

The top left-hand panel of Fig. 9b shows the log threshold ratios for *LD* discrimination around judgment points in the equiluminant plane. For a number of judgment points, the thresholds were higher by a factor of 2 or 3 for staggered sectors than for tests separated only in time. The results plotted in the middle and the right-hand panels of the top row show that *LD* discrimination thresholds around judgment points lighter or darker than the surround were higher by a factor of 3–6 for staggered sectors than for tests separated in time. The results for the points on the *LD* axis are shown in Fig. 8. The middle row of Fig. 9b shows the results for *RG* discrimination Within the equiluminant plane (left-hand panel) the thresholds for the two tasks were similar; the log threshold ratios therefore are near zero. Similarly, for judgment points in the planes spanned by the luminance and the equiluminant chromatic axes (middle and right-hand panels) the log threshold ratios are near zero. There was a slight tendency for the log threshold ratios to be higher for judgment points displaced toward Y or B, although the effect was not pronounced. For *YB* discrimination (bottom row), the thresholds for the two tasks were similar at almost all judgment points, as shown by the log threshold ratios near zero in all three panels. One point in the right-hand panel shows the only instance in which the threshold for tests separated in time was higher by more than a factor of 2 than the threshold for staggered sectors.

As is shown in Fig. 8 by the log threshold ratios near zero, the discrimination performances were similar for the two tasks when the tests differed along the *RG* or the *YB* lines. The luminance discrimination performances, on the other hand, were similar only around W for the two tasks. For luminance discrimination around judgment points ligher or darker than the surround, the performances for the two tasks were different, the thresholds being higher when memory was required. For discrimination tasks that require a bare minimum of memory, such as those described here, the efficiency of chromatic signals is unimpaired, while the efficiency of luminance signals is attenuated considerably.

Test colors could be placed in distinct perceptual categories for discrimination around W. This categorization was not possible for discrimination around the other judgment points. When the memory requirement was introduced, the thresholds for luminance discrimination increased for all the judgment points where perceptual categorization was not possible. The fact that the thresholds for luminance discrimination around W did not change when the memory requirement was added may be due to the availability of a perceptual categorization scheme. The discrimination of chromatic signals was largely unaffected by the addition of a memory requirement, even when perceptual categorization with respect to the surround color was not possible. This suggests a special role for chromatic signals in providing color information that is more stable during memory demands than is luminance information. In experiment 6 we show how perceptual categorization can attenuate the decrease in luminance discrimination performance caused by the introduction of a memory load.

EXPERIMENT 4. CONTROL FOR VISUAL PERSISTENCE OF CHROMATIC STIMULI

In experiment 3 we showed that luminance discrimination was attenuated with the addition of a memory requirement, while discrimination along chromatic lines was

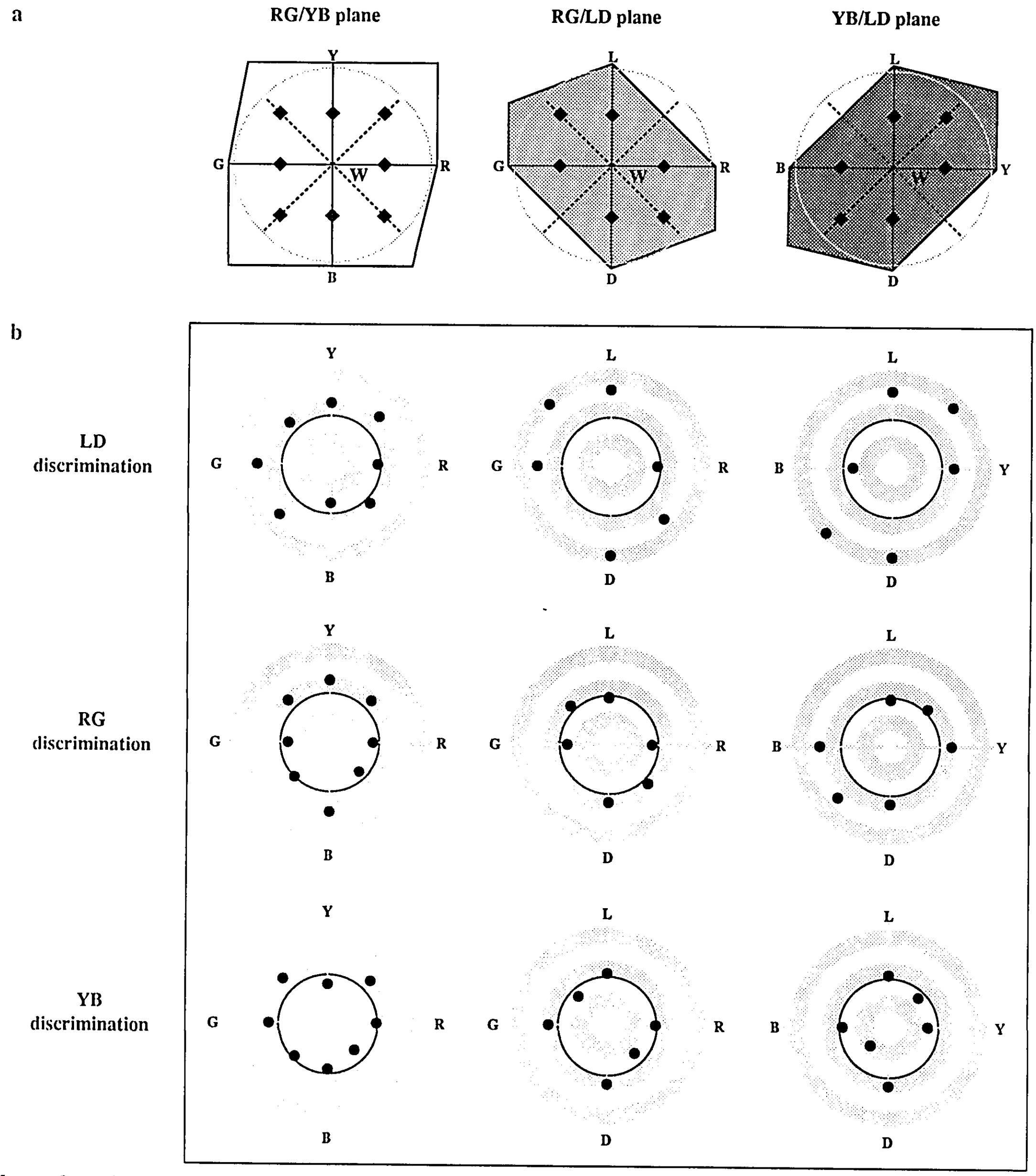


Fig. 9. Full set of results from experiment 3 for comparison of discrimination performance in the memory task with performance when tests were separated in time, excluding the comparison at W. The comparison was made for discrimination around judgment points distributed in the three color planes shown in panel a. The log threshold ratio is plotted as the distance along the radial line on which a judgment point was located. The results are shown in panel b. Values of zero, indicating that the thresholds for the two test conditions were identical, are plotted on the dark circle. Positive values, indicating that the thresholds were higher for the memory task, lie farther outside that circle, while negative values lie inside the circle. The magnitude of the index is represented as the distance from the dark circle. Concentric annuli are spaced in steps of 0.3 log unit. See also the legend of Fig. 6.

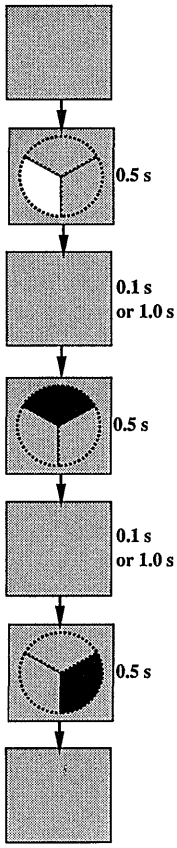


Fig. 10. Stimulus configuration used in experiment 4 to control for visual persistence of chromatic stimuli: staggered sectors with an added delay interval of 0.1 or 1.0 s between tests. The screen was a uniform W during the delay interval. Other specifications are as in Fig. 7.

not diminished. To determine whether the undiminished efficacy of chromatic signals was due to a greater visible persistence of chromatic stimuli, we added delays of 0.1 and 1.0 s between the test presentations for sectors staggered in both space and time. If discrimination performance for chromatic tests were undiminished owing to visual persistence, one would expect thresholds to increase as the duration of the delay is increased.

Spatial and Temporal Configuration

As is shown in Fig. 10, the stimuli were similar to the ones in experiment 3: three sectors of a 3° disk were shown sequentially for 0.5 s each. However, in this experiment a delay of either 0.1 or 1.0 s was added between the presentation of the sectors. The screen was returned to a uniform field for the duration of each delay interval. The observer had to determine whether the left- or the right-hand sector was different from the other two. Each trial was cued with three tones and was followed by a single tone. When the delay interval was 1.0 s long, the presentation of each sector was preceded by three tones. For this experiment, the three delay conditions 0, 0.1, and 1.0 s were run during separate sessions on one day for a given set of complementary judgment points.

Results

We compared the thresholds for tests separated by a delay with the thresholds when there was no delay between tests. We calculated an index reflecting the relative difference between the 0.1 s and the no-delay condition according to the following formula:

$$\log\left(\frac{\text{threshold for 0.1-s delay}}{\text{threshold for 0-s delay}}\right). \tag{3}$$

The index for the 0.1-s delay is plotted in Fig. 11 as triangles. The index comparing the thresholds for the 1.0-s delay and the no-delay condition was calculated according to a similar formula:

$$\log\left(\frac{\text{threshold for 1.0-s delay}}{\text{threshold for 0-s delay}}\right). \tag{4}$$

The index for the 1.0-s delay is shown as squares.

Positive values indicate that the thresholds for a given delay were elevated with respect to the thresholds for the no-delay condition. Figure 11 shows the results for judgment points on the cardinal axes. Discrimination was measured only for colors differing along the cardinal axis that a particular judgment point lay upon, as shown by the arrows in the corresponding diagrams. There was no systematic difference in the thresholds for delays of up to 1 s, indicating that the undiminished efficiency of chromatic signals found in the previous experiment was not due to visual persistence. Once memory is required, discrimination thresholds do not change systematically for delays of up to 1 s under the conditions described here. These results also show that adding power at lower temporal frequencies (introduced by the addition of the 1.0-s gap) did not systematically alter discrimination thresholds: changes in adaptation and response limitation phenomena are expected to be at a minimum for discrimination around W; therefore the similarity of the thresholds for different temporal conditions at W suggests that a shift in the power spectrum to lower temporal frequencies did not critically affect the discrimination thresholds within the range of spatial and temporal parameters used in these experiments.

EXPERIMENT 5. CONTROLS FOR THE EFFECTS OF ADAPTATION ON DISCRIMINATION

In experiment 3 we showed that thresholds for luminance discrimination increased when a memory requirement was introduced. This threshold elevation was apparent only for discrimination around judgment points removed from the adapting color. Even though the temporal patterns were the same for the memory task and for stimuli separated only in time, the two configurations differed in their spatial patterns. When stimuli were presented sequentially at the same location, adaptation occurring during the course of presentation could possibly have increased sensitivity to the difference between tests. When the sectors were staggered, each test was presented to a retinal region that was adapted to W since it had not previously been exposed to a test. The higher thresholds could thus have been due to response limitations within color mechanisms. Since adaptation to changes in luminance is more rapid than adaptation to changes in chromaticity,[40–42] the difference between the two pattern configurations would be greater for the *LD* tests than for the *RG* and the *YB* tests. This would produce results similar to those of experiment 3. To control for these possibilities we measured the discrimination thresholds for luminance during different states of adaptation in a new task requiring memory. The tests were presented sequentially at the same location but with an added gap of 1 s between them. To preclude perceptual categorization of tests with respect to the surround color, the latter was changed to W for the duration of each test.

Spatial and Temporal Configuration of Stimuli

As a baseline, thresholds were measured for tests separated in time as described in experiment 1 and shown schematically in Fig. 12a. The middle sector of three equal sectors of a circle with a 3° diameter took on the test colors for three contiguous time intervals. Thresholds were also measured with a similar stimulus to which a 1-s gap between test presentations was added, during which the screen returned to W. In this condition, memory was required for the comparison of tests. This stimulus is shown in Fig. 12b. These two spatiotemporal configurations were employed to measure luminance discrimination around the points L, D, and W, while the surround, and adaptation, remained at W throughout the experiment. In an additional set of conditions, the observer was adapted to the luminance of the judgment point (L or D); the color of the screen remained at that value except during the presentation of a test, when the color of the surround was changed to W. This is shown in Fig. 12c. In that way, the surround color was at W whenever test colors around judgment points L or D were presented, so that both tests were either darker or lighter than the surround during a test interval. This spatiotemporal configuration ensured that tests could not be placed in distinct perceptual categories with respect to the surround color. The retinal area exposed to the tests was never exposed to W, so that its adaptation state remained at or near the value of the judgment point. Trials were separated by 10-s intervals to ensure that the adaptation state of the entire retinal area exposed to the screen could return to the luminance of the judgment point tested. The discrimination thresholds around each judgment point were measured in separate experimental sessions on one day.

Results

Figure 13 shows the results for luminance discrimination around points L, D, and W as changes in cone excitations required for the discrimination threshold. The error bars indicate one standard error of the 12 reversal points of the staircases. The task permitting a side-by-side comparison in time is labeled 0 s. The condition requiring

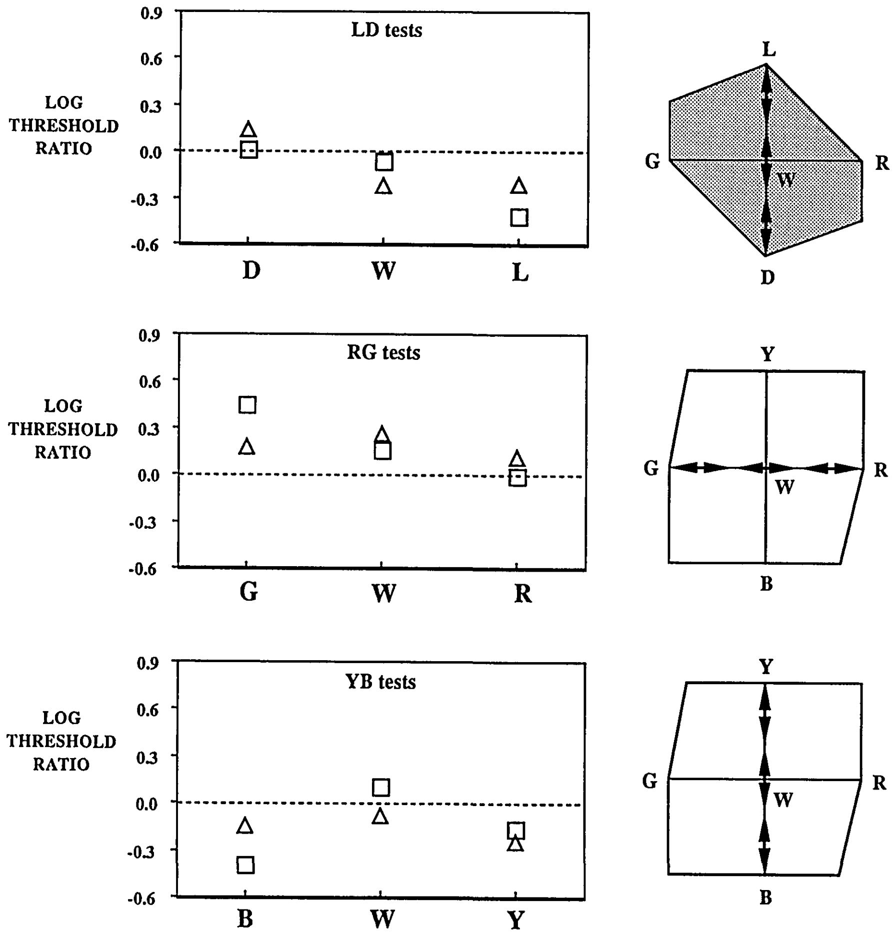


Fig. 11. Results from experiment 4: comparison of thresholds for staggered sectors separated by a delay with thresholds when no delay was added. Triangles: log of the ratio of thresholds for 0.1-s delay to thresholds for no delay [see formula (3)]. Squares: log of the ratio of thresholds for 1.0-s delay to thresholds for no delay [see formula (4)]. Positive values indicate that the thresholds were higher for the conditions with the added delay, while a value of zero indicates that the thresholds were identical. Results are shown for discrimination around judgment points on each of the cardinal axes.

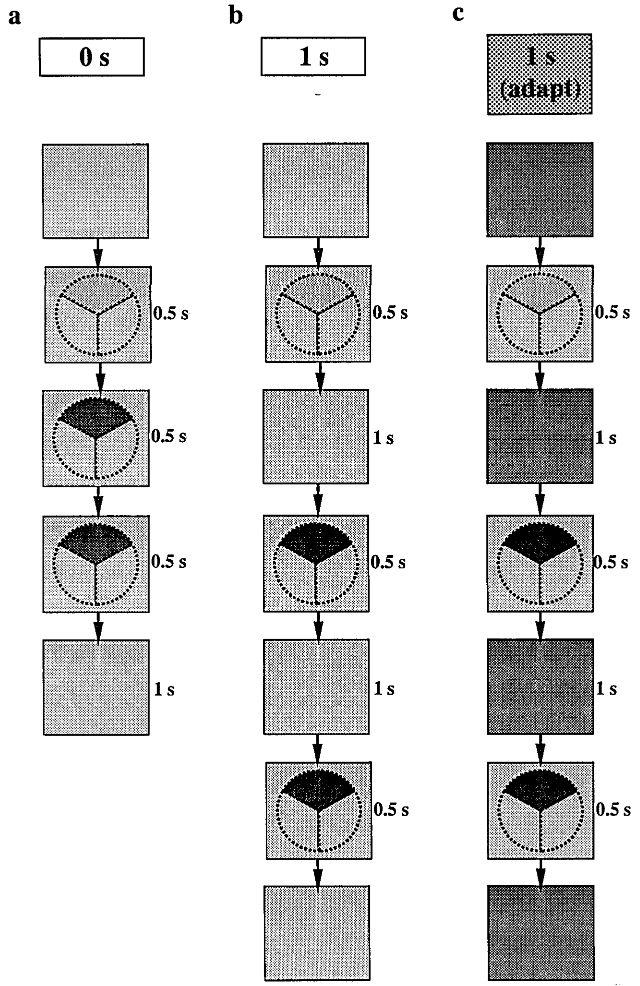


Fig. 12. Stimulus configuration used in experiment 5 to control for adaptation. Boxed labels serve to identify discrimination thresholds for each condition in Fig. 13. a, Tests separated in time. Tests followed one another without intervening delay. Adaptation was to W. b, Tests separated in time but with an intervening delay of 1 s, which introduced a memory demand for the comparison of tests. The screen was uniform during the delay interval. Adaptation was to W. c, Tests separated in time with an intervening delay of 1 s. Adaptation was to the color of the judgment point around which discrimination was measured. The color of the surround was shifted to W during the presentation of each test. During the delay interval the screen returned to the adapting color of the judgment point.

memory is labeled 1 s. For both of these conditions the observer was adapted to W, and the surround remained at that color throughout the experiment. Luminance discrimination around W was approximately the same for the two temporal configurations (middle panel). The difference in temporal frequency components between the two tasks was therefore not a critical factor under the present experimental conditions. The thresholds around points L and D were different for the two temporal configurations: the thresholds were higher for the task requiring memory. When tests followed one another without a temporal gap, adaptation to the luminance of the judgment point may have made the difference between test colors more detectable. The increase in threshold when a 1-s gap was added may have been due to the fact that adaptation returned to W during the gap interval. The results for the condition in which the observer was adapted to the luminance of the judgment point are labeled 1 s (adapt). For discrimination around L, thresholds were similar to the 1-s condition whether the observer was adapted to the luminance of the judgment point or to W. The discrimination thresholds around D were significantly different ($p < 0.01$, two-tailed t-test) for the adapted and the unadapted 1-s conditions. This suggests that adaptation may have a small effect on discrimination performance in the absence of cues for perceptual categorization. Thresholds were smaller by only a factor of 1.5 for the adapted condition, which is not sufficient to account for the large threshold changes of a factor of 3–6 found in experiment 3 with the introduction of a memory requirement. Therefore the increase in discrimination thresholds observed after the introduction of a memory requirement was probably not due to differences in adaptation states.

In this experiment tests could be placed into distinct perceptual categories only for discrimination around W. When adaptation was to L or D, the surround color was changed to W during the presentation of each test to preclude such a categorization. In the next experiment we explored the role of perceptual categorization in color discrimination by shifting the color of the surround from the adapting color W to the color of the judgment point during each test presentation.

EXPERIMENT 6. USE OF BACKGROUND AS REFERENCE FOR COLOR CATEGORIZATION AND DISCRIMINATION.

In experiments 3 and 5 we showed that, when the surround was the color of the judgment point throughout a trial, discrimination performance was the same for tasks requiring memory and for tasks permitting a side-by-side comparison of tests in time. This was the case for discrimination around W, in which case tests could be placed into distinct perceptual categories since the test colors were points chosen symmetrically around W in the color space. For luminance discrimination, one test was lighter and the other was darker than the surround, and the categorical change in the relationship of the test to the surround color may have helped in discrimination. Adding a memory requirement to a task that could initially be performed as a side-by-side comparison elevated luminance thresholds only around judgment points lighter or darker than the surround but not around W. In this experiment we explored the use of perceptual categorization under the conditions in which discrimination performance was degraded. Specifically, adaptation was maintained at W while discrimination was measured around a number of judgment points removed from W. As a baseline, thresholds were measured for a memory task and for a task permitting a side-by-side comparison in time. Then, in an additional condition, the surround was shifted to the color of the judgment point around which discrimination was being measured. This was done only during the presentation of a test so as to keep changes in adaptation to a minimum. Exposure of the retinal region on which the test was imaged was the same whether the surround color was shifted or not. The adaptation state of this retinal area was thus only minimally affected by the changes in surround color. Because the surround color was shifted

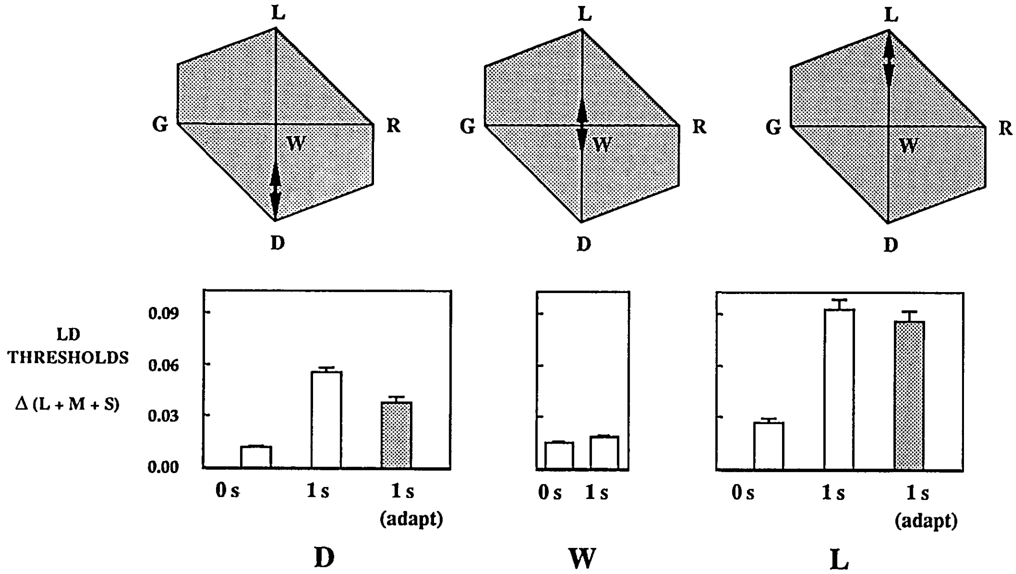


Fig. 13. Results from experiment 5 for luminance discrimination around points L, D, and W as changes in cone excitation required for discrimination thresholds. The error bars indicate one standard error of the 12 reversal points of the staircases. The light bars show the results for discrimination when the observer was adapted to W. The stimuli were separated in time and followed one another with no intervening delay (0 s) or were separated by a 1-s delay. The shaded bars show the results for discrimination when the observer was adapted to the value of the judgment point. The color planes show the judgment points and color lines along which the tests differed for the corresponding panels.

to the value of the judgment point, an observer could place the tests into distinct categories with respect to it. We tested whether perceptual categorization would enhance discrimination performance around judgment points removed from the adapting color and, in particular, whether it could attenuate the loss in performance seen for luminance discrimination owing to the introduction of a memory requirement.

Spatial and Temporal Configuration of Stimuli

The stimulus consisted of the middle of three equal sectors of a circle with a 3° diameter. The test colors were presented sequentially at the same location. As a baseline, thresholds were measured for tests presented sequentially with no temporal gap (Figs. 14a and 14c), which permitted a side-by-side comparison of tests across time. This is termed the 0-s condition. To introduce a memory requirement we added a 1-s gap between tests, during which the screen returned to W. This is shown in Figs. 14b and 14d. Both delay conditions were tested under two background conditions: in one the surround remained at W throughout a trial (Figs. 14a and 14b). In the other conditions the surround shifted to the color of the judgment point around which discrimination was measured during the presentation of each test (Figs. 14c and 14d). During the 1-s delay interval the screen returned to a uniform W. Trials were presented 10 s after the observer's response. Conditions with and without a shift in the surround color were interleaved randomly.

Results

The letters on the horizontal axes of the graphs shown in Fig. 15 indicate the judgment points around which discrimination was measured. Each row of plots shows the results for discrimination along one color line. The results are shown as changes in cone excitations required for the discrimination theshold along the axis on which a judgment point was located; e.g., for judgment point L tests were along the *LD* line. The light bars represent the results for the conditions in which the surround remained at W throughout the trial. The shaded bars show the results for the conditions in which the surround was shifted to the color of the judgment point. Vertical bars are equal to one standard error.

The middle panel in each row shows the results for discrimination around W along a given color line. In that condition the surround and the judgment point were the same color W. The thresholds were slightly higher when the tests were separated by a 1-s delay than when there was no delay. This was the case for the three color directions tested around W.

The results for discrimination along the luminance axis are shown in the top row of Fig. 15; the right-hand graph shows the results for discrimination around judgment point L. When the surround remained at W and no delay was added (light bar, 0 s), the thresholds were higher than for luminance discrimination around W. Adding a 1-s delay between tests while the surround remained at W more than doubled the threshold. For tests requiring memory, changing the surround to the color of the judgment point (shaded bar, 1 s) lowered the thresholds by a factor of approximately 1.8. Shifting the surround color to the judgment point did not alter the thresholds much when the tests were not separated by a delay (shaded bar, 0-s condition). This suggests that the threshold difference seen between L and W in the 0-s condition was due mainly to response limitations in the luminance mechanism and not to an inability to place tests into perceptual categories. A similar pattern was seen for luminance discrimination around point D, where threshold changes were even more pronounced. The enhanced discrimination obtained when the background color was shifted was probably not due to adaptation, since the results of experiment 5 showed that a controlled adaptation to the judgment point failed to lower thresholds when the surround color could not serve as a reference for categorization.

The results for chromatic tests are shown in the middle and the bottom rows. Adding a 1-s delay between tests while the surround remained at W did not systematically elevate the thresholds. Shifting the surround to the color of the judgment point lowered the thresholds somewhat for all the conditions; the dark bars in the plots are shorter than the corresponding light bars, for both when tests were separated by a delay and when no delay was added.

The results show that shifting the color of the surround could help to attenuate sensitivity losses for *LD* discrimination when a side-by-side comparison of tests was not possible. Even for chromatic tests, in which the addition of a memory requirement did not systematically alter the thresholds, shifting the surround color lowered the thresholds slightly at all the judgment points tested.

DISCUSSION

An analysis of the efficiency of luminance and chromatic signals can be made only in the context of a given task and stimulus configuration. In the experiments described here we began by examining the conditions in which chromatic signals were already more efficient than *LD* signals. Even for conditions in which chromatic signals encountered response limitations, *RG* discrimination was still more than twice as efficient as luminance discrimination. Introducing a memory load by staggering stimuli in space and time made the difference in efficiencies for the two types of signal even greater. These experiments help to distinguish between the threshold differences found between simultaneous spatial and successive temporal comparisons on the one hand and the threshold elevation that is due to the introduction of a memory demand on the other. Newhall *et al.*[6] found that discrimination thresholds were higher for a memory task than for a simultaneous spatial comparison. For the spatiotemporal configurations used in this study, the thresholds were generally higher for a temporal comparison than for a spatial comparison, even in the absence of a memory demand. The addition of a memory demand then further elevated luminance discrimination thresholds but hardly affected chromatic thresholds.

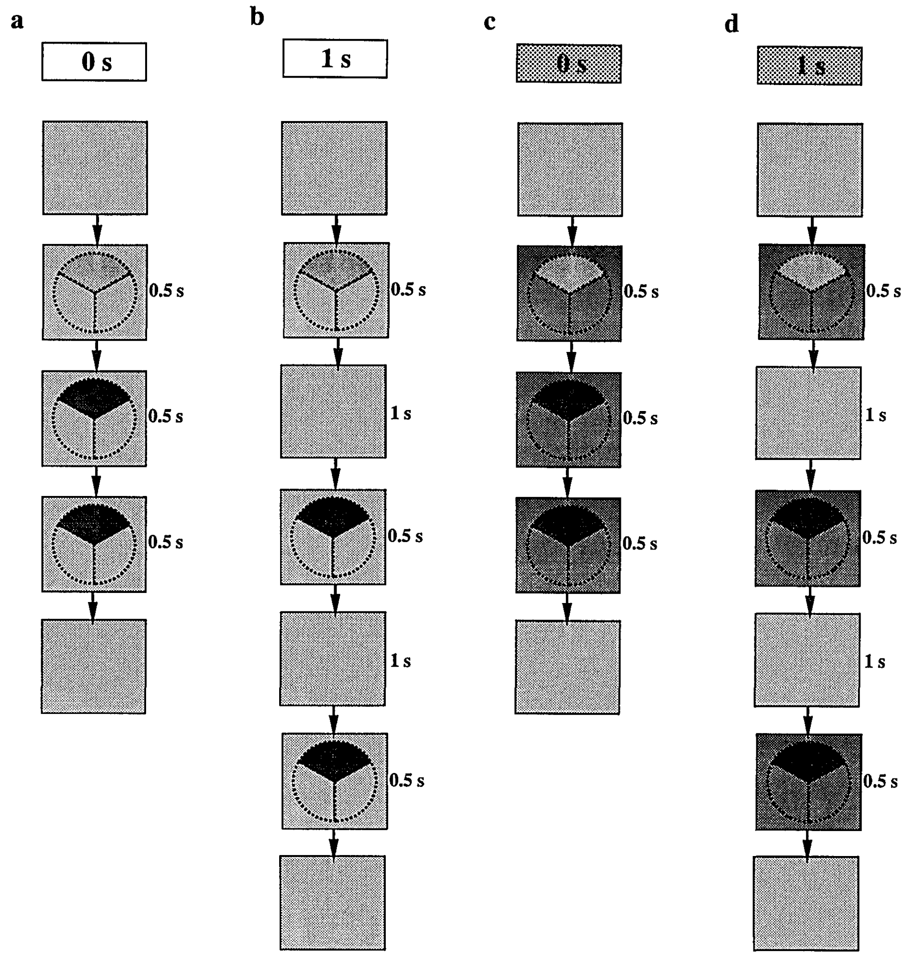


Fig. 14. Stimulus configurations used in experiment 6 to examine the use of the surround color as a reference for color categorization and discrimination. The boxed labels identify the results for each condition in Fig. 15. a, Tests separated in time, with no intervening delay. The surround remained at W throughout a trial. b, Tests separated by an intervening delay of 1 s, so that memory was required for their comparison. The screen was uniform during the delay interval. The surround remained at W throughout a trial. c, Tests separated in time, with no intervening delay. The color of the surround was shifted to the value of the judgment point around which discrimination was measured during the presentation of each test. The test colors were thus placed symmetrically around the surround color. The screen returned to a uniform W at the end of each trial. d, Tests separated in time by an intervening delay of 1 s. The color of the surround was shifted to the value of the judgment point during the presentation of each test. The screen returned to a uniform W during the delay interval and at the end of each trial.

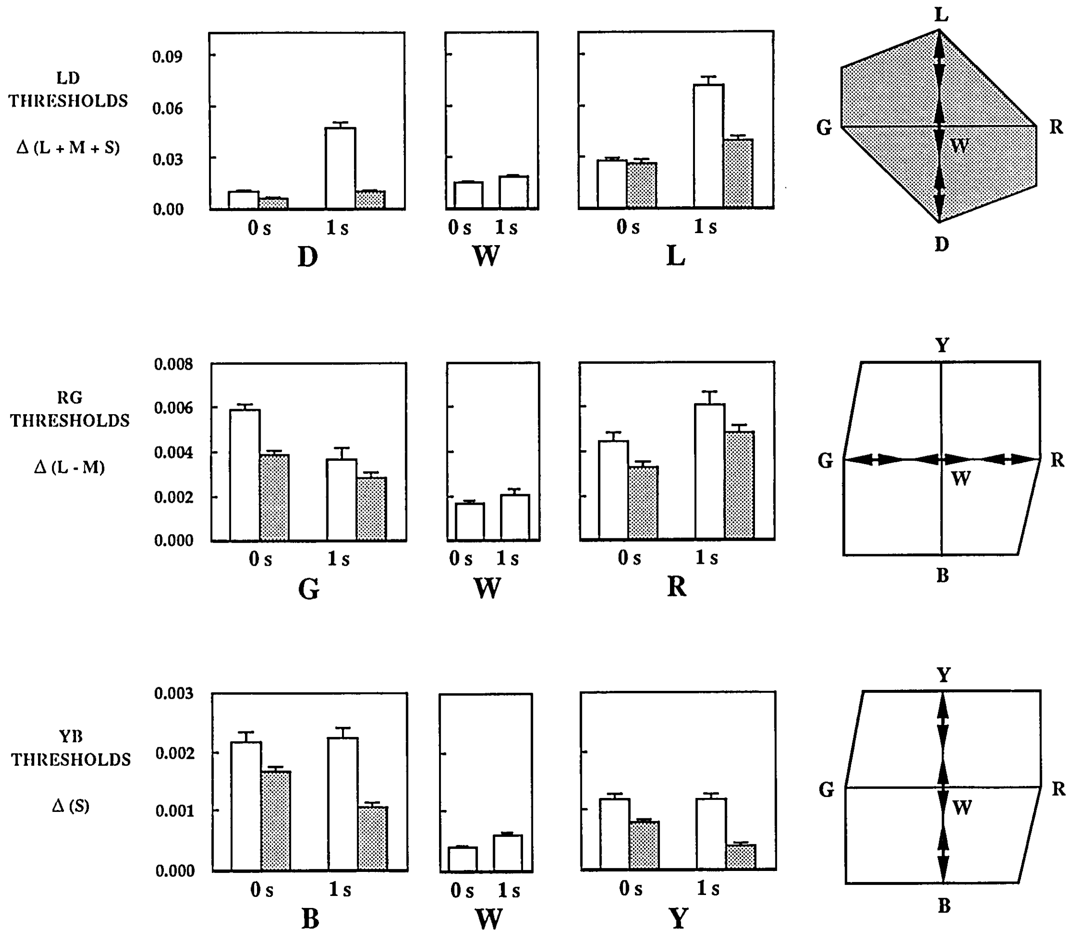


Fig. 15. Results from experiment 6: the discrimination thresholds for the four test conditions in Fig. 14 are plotted as changes in cone excitations for tests along the axis on which the judgment points were located. Light bars: the surround remained at W throughout a trial. Shaded bars: the surround shifted to the color of the judgment point during each test. The no-delay (0-s) and the 1-s-delay conditions are labeled. The error bars indicate the standard error of the 12 measurements made with the staircases. The color planes to the right of the sets of graphs indicate the corresponding judgment points and the color lines along which discrimination was measured.

In our experiments we controlled for a number of potential ancillary phenomena. The effects of response limitations and adaptation were accounted for by comparing relative threshold differences between tasks at the same judgment points. Furthermore, controlled changes in adaptation state also did not alleviate the diminished luminance discrimination encountered in a memory task as long as conditions were such that a perceptual categorization of tests with respect to the surround color was not possible. In addition, the task requiring memory in experiment 3 had the same temporal components as the task permitting a side-by-side comparison of tests in time. Therefore chromatic signals appear to be effective in simple color discrimination tasks requiring even the smallest amount of memory. The inefficiency of luminance signals in a memory task can be countered by introducing information that permits test colors to be placed into distinct perceptual categories.

The spatiotemporal conditions of experiment 3 (see Fig. 7), in which the sectors of a circle were staggered in space and time, are functionally equivalent to tracking the identity of a moving stimulus. To clarify this, one can think of a variant of the experiment: a test stimulus, say, a circle, is presented at one location. The color of this circle is the reference color. After 0.5 s this circle vanishes, taking on the color of the surround, and is replaced by two test circles, one to either side of it. One of these test circles is the same color as the reference circle, while the other differs in either chromaticity or luminance. The observer is then asked in which direction the original reference circle appeared to move, i.e., one has to determine which of the two test circles is identical to the reference. When the test colors differ by less than the threshold amount, the observer will respond correctly on only 50% of trials. The results of experiment 3 indicate that this task can be performed more accurately for chromatic differences than for luminance differences. Our results therefore provide an empirical measure of the ability to track the identity of moving stimuli, which can be related to the phenomenal observations of Cavanagh.[46]

In this study we have examined "color memory,"[6] i.e., memory for color in general. This is different from "memory color,"[47] which is the remembered color that is regarded as an essential property of familiar objects. The connection between color memory and memory color deserves a study of its own. To describe the appearance of objects completely, one requires more attributes (e.g., transparency and glossiness) than are required for a description of the appearance of lights.[48] However, even an informal survey indicates that memory colors of familiar objects are generally specified in terms of hue and saturation. The discrimination task used in this study can alternatively be viewed as an identification task; i.e., what is the range of variation possible in the appearance of a stimulus within which it is identified as the same stimulus by an observer? Chromatic thresholds were not elevated in memory tasks, suggesting that the chromatic component of the light signal from an object is of considerably more use than the brightness component in identifying the object over viewings separated in time. The color temperature of ambient sunlight can vary over seasons and even during a day,[49,50] but this variation is a minute fraction of the change in illuminance during a day. The light incident from an object over separate viewings would therefore be expected to exhibit a smaller variation in spectral composition than in brightness. The greater visual capacity to remember chromaticities than brightnesses seems to be matched to this physical phenomenon.

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