Task-dependent color discrimination

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When an observer's ability to discriminate colored objects is estimated from the variability in color matches, the observer inspects adjacent visual fields carefully and makes considered judgments. Color discrimination does not always take place under such viewing conditions. When color video displays are used in time-critical applications (e.g., head-up displays, video control panels), the observer must discriminate among briefly presented targets seen within a complex spatial scene. We compare color-discrimination thresholds by using two tasks. In one task the observer makes color matches between two halves of a continuously displayed bipartite field. In a second task the observer detects a color target in a set of briefly presented objects. The data from both tasks are well summarized by ellipsoidal isosensitivity contours. The fitted ellipsoids differ both in their size, which indicates an absolute sensitivity difference, and orientation, which indicates a relative sensitivity difference.

INTRODUCTION

When we compare the color of the paint on a car door with the color of the paint on the main body, we can focus our attention on a small part of a static visual scene and closely inspect the components. But when we drive a car, we can only glance briefly at the dashboard to check the colored indicators. The visual scene of the dashboard is not static, and we cannot focus our attention on a small part of the display. Rather, we must be ready to notice changes at any indicator position. We believe that it is important to compare observers' ability to discriminate color differences in these different tasks.

Color-discrimination metrics currently recommended by the CIE[1,2] are based in part on data reported by Brown, MacAdam,[3–6] and others obtained from color-matching variability. The Brown–MacAdam laboratory procedure models natural viewing conditions in which the observer has time to make a close visual inspection of a pair of objects in a spatially simple scene.

In this paper we compare discrimination thresholds measured in two different ways. First, we report data from a procedure that models viewing conditions in which the observer must make a judgment hurriedly when presented with a complex display. In our procedure subjects were briefly presented with an array of colored squares at randomly selected positions on a calibrated monitor. For half of the trials all the presented squares had the same tristimulus coordinates. For the remaining half of the trials one of the colored squares (the target) was slightly different from the remaining colored squares (the distractors). Observers reported whether all the squares were the same (noise trials) or one was different (signal trials), and d' was calculated from the responses. Second, we report data that were collected with the Brown–MacAdam color-matching procedure.

We summarize four main conclusions based our data. First, in the discrimination task, the set of points discriminable at a d' level of 1 falls near the surface of an ellipsoid. This result corresponds to Brown and MacAdam's observation that the contour 1 standard deviation about the mean color-match setting falls near the surface of an ellipsoid. Therefore, we summarize discrimination thresholds using a discrimination ellipsoid, and we summarize color-matching variability using a color-matching ellipsoid. Second, discrimination ellipsoids vary considerably as the target falls at different retinal locations, even for small differences in the retinal location. Third, when the average spacing between the target and distractors is held constant, the discrimination ellipsoids are independent of the number of distractor objects. Fourth, the discrimination ellipsoids that we measure are significantly different from color-matching ellipsoids derived from the Brown–MacAdam procedure.

METHODS

Introduction

On each trial the subject saw a 150-msec flash that was composed of a variable number of colored squares. The subject's task was to report whether he perceived all the squares to be of the same color appearance or whether one appeared slightly different from the others. On one half of the trials one of the squares was set to a different color coordinate from the others (signal trials). We call this square the target item. On the remaining one half of the trials all the squares were set to the same color coordinate (noise trials). If a square is not the target item, then it is a distractor item. The subject was uncertain where the squares would appear on the screen and how many squares would be present. When a target was present, the subject was uncertain about the relative location of the target among the distractors.

An individual trial was constructed as follows. First, a distinguished position, which we call the central point, was selected from a subset of the set of ten by ten grid points. The grid points were separated by 0.55 deg in both the row and column directions. The central point was chosen from the points in the central grid. These points are outlined by the dark solid line in Fig. 1 and fall in the central 2 deg of the visual field. The positions of the distractor items were selected randomly from the set of positions in the distractor grid. The distractor grid was centered at the central point, which varied from trial to trial. At each point in the distractor grid an item was presented with probability one half. No

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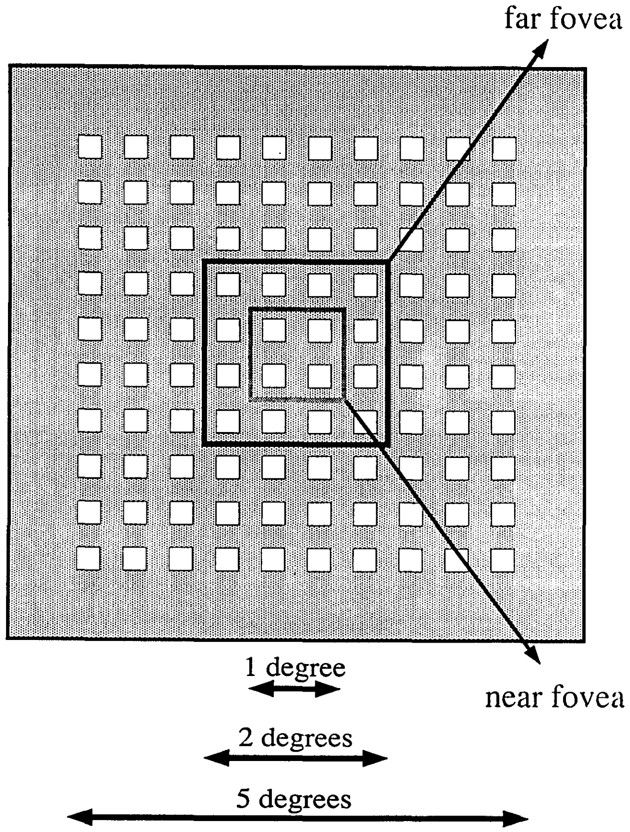

Fig. 1. Possible object positions. The target and distractor items were presented at one of the grid points. The central point always fell within the central square, indicated by a dark solid line. The distractor grid surrounded the central point. See the text for further details.

distractor items were presented outside the distractor grid. The subject sat 138 cm from the display monitor. Both the target and distractor items were 0.25-deg squares and were centered on the grid points. The central point was presented in all trials and was the target item in signal trials.

We ran two blocked conditions that differed only in the size of the distractor grid. In one condition, the distractor grid around the central point was 3 × 3 (9 total points). In the other condition, the distractor grid around the central point was a 7 × 7 grid (49 total points). When the distractor grid is 3 × 3, the expected total number of objects presented is 5, and the variance is 2. When the distractor grid is 7 × 7, the expected total number of objects presented is 25, and the variance is 12.

In preliminary experiments we found that sensitivity to color differences varied with the central-point position. We will report separately the color-discrimination sensitivity of central points within 1 deg of the central fovea (outlined by a light gray line in Fig. 1) and the central points in the concentric box region extending from 1.0 deg to 1.5 deg in the central fovea. We call these regions the near fovea and the far fovea. Within any block, one half of the trials were randomly selected with a central point in the near fovea, and one half of the trials were selected with a central point in the far fovea.

Our preliminary experiments, as well as other data,[7] indicate that the separation between a target and its nearest distractor strongly affects observers' sensitivity to color differences. If N distractors are displayed at random positions on a fixed grid (e.g., Treisman[8]), then as the number of stimuli increases the modal spatial separation between a target and the closest distractor item decreases. Experiments with the same average number of distractors but different separations do not yield equal color-discrimination thresholds; when the distractor items are closer to the target item, discrimination improves. In the experiments that we report here, the separation between the target item and its closest distractor item remains constant as we vary the distractor set size.

Monitor Calibration

We presented our stimuli on a Barco display (Model CDCT 6351) that was run at 87 Hz, noninterlaced. The display was controlled by a graphics card in an IBM PC-AT. We compensated for the nonlinear relationship between frame-buffer values and display output by using the following procedure. First, for each frame buffer we measured the intensity output from the monitor at each of the 256 levels at the screen center and placed these values in look-up tables. We used the look-up tables to determine the frame-buffer value required to obtain a desired output level. To correct for variations in signal-output strength at different spatial locations on the screen, we measured the output of the monitor when the frame buffer was set to 255 at several positions away from the center. We used the ratio of the output at the off-center position to the output at the center position to define a spatial correction factor. When an object was displayed at a particular spatial position, we divided the desired output level by the spatial correction factor for that position and used this number to set the frame-buffer value.

Our method assumes that the nonlinear relationship between frame buffer and output level is the same at all spatial locations. We also assume that the spectral power distributions of the phosphors are the same at all spatial locations up to a scale factor. We used Brainard's[9] procedures to test these assumptions, and we find them to be true to within a few percent for our display equipment.

The characteristics of our monitor did not change significantly over time. Calibrations repeated several months after the start of the experiment were within 3% of the original measurements.

Color Representation

Using the calibrated color signal from the monitor, we report our color measurements in the receptor coordinate frame defined by the Smith–Pokorny fundamentals[10] as described in Boynton's table.[11,12] We normalized the receptor responses so that each cone class has a peak sensitivity of one. Each axis in this coordinate frame is proportional to the quantal absorptions of a cone class.

Threshold Estimation

We report data from two subjects. One subject, AF, is highly practiced in psychophysical data collection, and the other, TG, became so. We measured sensitivity to color differences between the target and distractors in at least 20 color directions. These directions were chosen to fall within three separate planes in color space as defined by each of the pairs of receptor axes. We estimated discrimination threshold for target items in different color directions in separate blocks of trials. Thresholds were estimated by using an adaptive

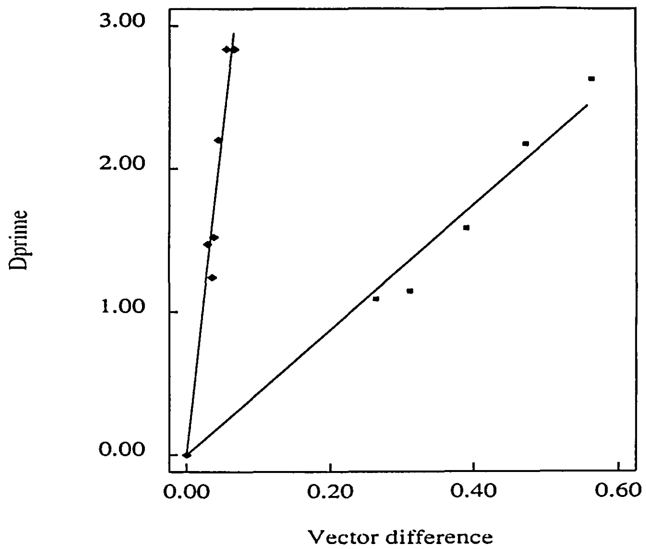

Fig. 2. Linear estimate of d' versus vector difference for two color directions. The points are d' calculated at vector-difference lengths that had ten or more signal trials. The lines are the weighted, linear least-squares fit. The weighting of each data point is the square root of the number of trials at that level.

multiple-staircase procedure. Call the three-dimensional vector representation of the distractors ρ_d, the vector representation of the target ρ_t, and the color difference vector $\rho = \rho_d - \rho_t$. When the observer made two correct responses on signal trials, the color-difference vector was scaled by a factor of 0.8. Whenever the observer made an error, the color-difference vector was scaled by 1/0.8. A block consisted of 256 trials, one half signal trials and one half noise trials. Individual data points are based on one or two blocks of trials.

We determine the color-discrimination threshold in a measurement condition as follows. For each color direction we estimated d' as a function of the magnitude of the color-difference vector. The hit rate is determined from only signal trials at a single vector-difference length, while the false alarm rate is determined from all the noise trials. To estimate d' from these yes/no data we assume that the internal effect of the signal and noise distributions are normal and that the two distributions have equal variance. Under these assumptions d' is estimated from the normal deviates of the hit and false alarm probabilities by using the equation $d' = z(\text{hit}) - z(\text{false alarm})$. Figure 2 plots two typical curves of d' versus vector-difference length. We include only target item levels at which ten or more signal trials were presented. We estimate the magnitude of the color difference at which d' equals one by using a linear least-squares fit in which the contribution of each point is weighted by the square root of the number of trials presented at that level. The results are not sensitive to the various weighting procedures that we tried. Following Nachmias and Kocher[13] we also evaluated power-law relationships between d' and vector length. For our conditions, however, a linear relationship provides the best approximation.

Ellipsoid Fitting Procedure

We summarize discrimination performance by fitting an ellipsoid to the discrimination thresholds. Ellipsoidal approximations were estimated by using the methods described in Poirson *et al.*[12] The fitting procedure described in that paper returns the coordinate frame in which the data points fall closest to a unit sphere. It follows that the error in the fit is the actual length of the threshold vector in the transformed coordinate frame minus one. Call the error for a threshold point in the nth color direction e_n, and define the overall error as

$$\mathbf{E} = \left(\frac{1}{N}\sum_{n=1}^{N} e_n^2\right)^{1/2}, \tag{1}$$

where N is the number of color directions. The formula computes the root-mean-squared difference between the observed and expected magnitude of the threshold vectors. In the coordinate frame where the best-fitting ellipsoid is a unit sphere, **E** describes the typical percent error between the ellipsoidal approximation of the data and the data itself.

We measured discrimination performance for distractors at three positions in color space. In receptor coordinates these positions were (1.71, 1.48, 1.96) (bluish), (3.10, 2.65, 1.84) (white) and (4.81, 4.13, 3.80) (pink). Equivalently, in (xyY) coordinates (Y in cdm^{-2}), these positions were (0.273, 0.243, 8.50), (0.316, 0.336, 16.00), and (0.297, 0.296, 25.50). All distractor items and target items were presented on a dark background.

RESULTS

Introduction

We summarize several features of our color-discrimination measurements. First, the discrimination thresholds are well fitted by ellipsoids. The quality of the fit is comparable with the quality of the fit to detection data.[12,14] Second, the parameters of the estimated ellipsoids are different when the central point is in the far fovea (1.0–1.5 deg) compared with when the central point is in the near fovea (central 1.0 deg). The difference is principally an increase in the size of the discrimination ellipsoid in the far fovea compared with the near fovea. Third, the ellipsoid parameters do not differ between the two distractor grid sizes that we used. Finally, ellipsoids estimated from data collected using our task are different from color-matching ellipsoids[3,4] estimated from data collected using the bipartite field color-matching experiment.

The Ellipsoidal Approximation

We estimated three-dimensional ellipsoids for each of 12 data sets. Recall that from the ellipsoid fitting procedure we obtain a coordinate frame in which the color-difference vectors fall closest to a unit sphere. If there is no error in the ellipsoidal fit, then the magnitude of the color-difference vectors in this coordinate frame will all be one. In Fig. 3 we plot a frequency distribution of the lengths of the 280 thresholds measured in the coordinate frame in which the data fall closest to a sphere of radius one. Seventy-five percent of the data points fall within 0.1 log unit of unit length. The frequency distribution plotted in Fig. 3 is virtually identical to distributions reported by Poirson *et al.*[12] and Poirson and Wandell,[15] who fitted ellipsoids to thresholds data collected under different viewing conditions.

In Fig. 4 we plot the thresholds and corresponding ellip-

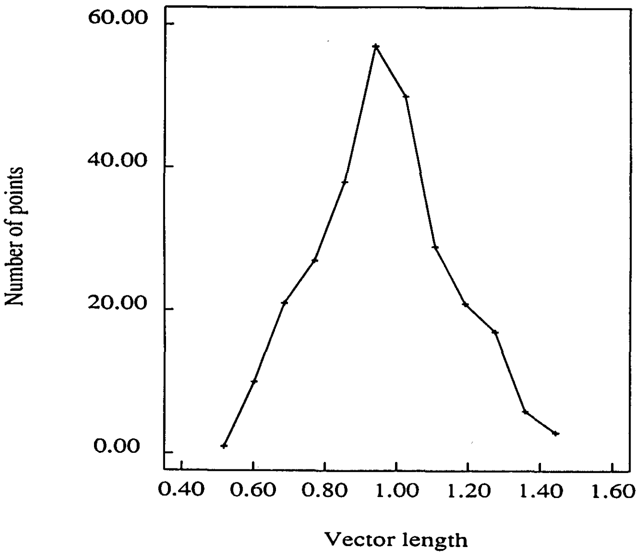

Fig. 3. Frequency distribution of the lengths of the data points in the coordinate frame in which the data fall closest to a sphere of radius one.

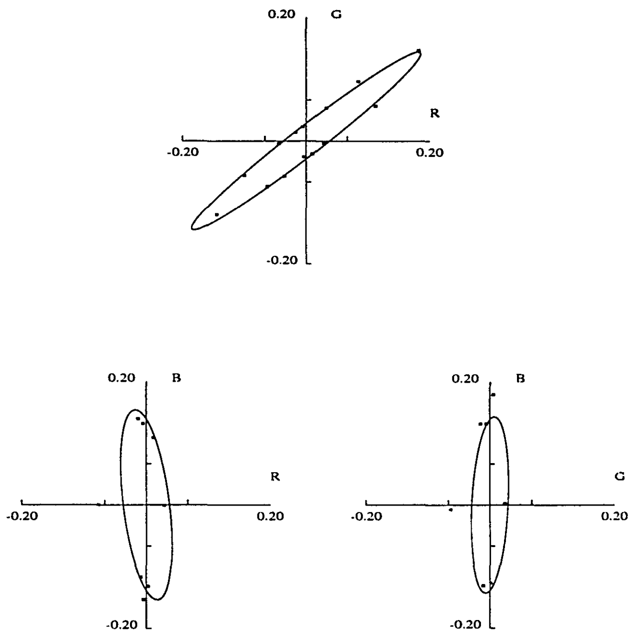

Fig. 4. Thresholds and ellipsoidal cross-sections fitted in the three color planes used in collecting data. Data are from near-fovea trials, distractor grid 3 × 3, observer AF, and distractor color location (1.71, 1.48, 1.96). The value of E for this data set is 0.11.

soidal fit for one experimental condition. These thresholds were measured in the near fovea for observer AF, using a 3 × 3 distractor grid at distractor color location (1.71, 1.48, 1.96). We plot the thresholds in three planes aligned with each pair of receptor axes. The curves drawn near the data points in Fig. 4 are cross sections of the best-fitting ellipsoid.

In Fig. 5 we plot the spectral-sensitivity curve that was derived from this ellipsoid. This curve was estimated by using the procedure described by Poirson *et al.*[12] Notice that the spectral sensitivity for this discrimination task shows three lobes that are characteristic of detection based on opponent-color mechanisms. The spectral sensitivity is similar to spectral sensitivities estimated using long-duration test flashes on neutral backgrounds.[12,16,17]

Effect of Retinal Location

Figure 6 compares thresholds in the near- and far-fovea conditions for observer TG at distractor color location (1.71, 1.48, 1.96) and distractor grid size 3 × 3. The distractors

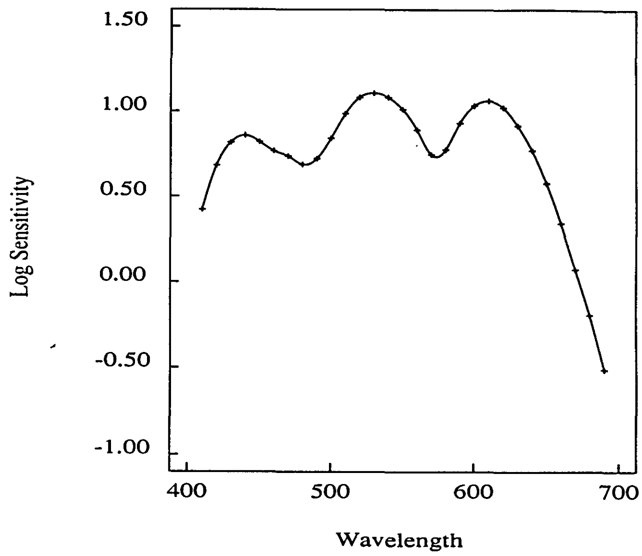

Fig. 5. Spectral sensitivity derived from ellipsoidal fit to data collected by observer AF (shown in Fig. 4).

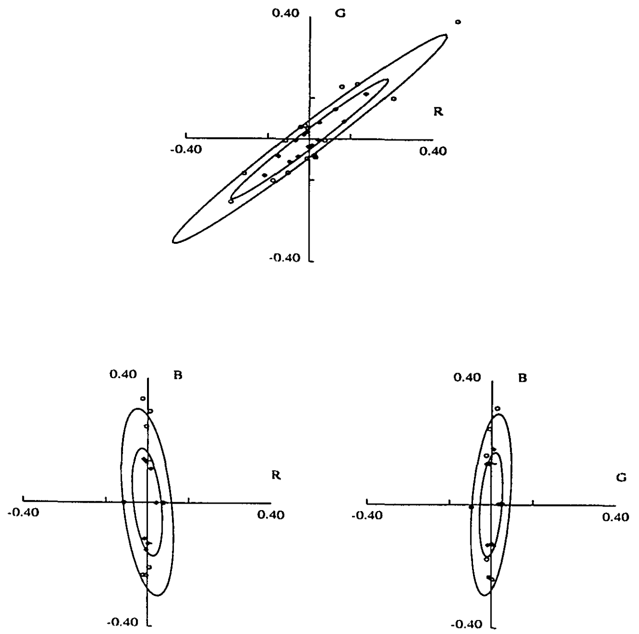

Fig. 6. Comparison of the near-fovea data (filled diamonds) and far-fovea data (open circles); subject TG. The distractor color location was (1.71, 1.48, 1.96), and the distractor grid was 3 × 3. The smooth curves are the cross sections of the best-fitting, three-dimensional ellipsoid calculated using all the points. The calculation of these fits was constrained so that the two ellipsoids are scaled copies of each other. The root-mean-squared error E of the ellipsoidal fit to the data is 0.195 for the near-fovea data and 0.229 for the far-fovea data. The scaling factor for these data is 1.74.

appeared bluish gray. Recall that we defined the near-fovea region to be the four central positions within 1.0 deg of the fixation position and the far fovea to be the 12 positions within 1.0–1.5 deg.

We evaluated the change in sensitivity by fitting the thresholds measured in the near and far fovea in two different ways. First, we obtained the best-fitting ellipsoid to each data set independently. This fitting procedure requires 12 parameters, 6 for each of the ellipsoids. Then, we obtained the best-fitting ellipsoids to both data sets under the constraint that the two ellipsoids must be identical up to a single scale factor. This fitting procedure requires seven parameters, six to define the near-fovea ellipsoid and one parameter to define the scale factor for the far-fovea ellipsoid.

The data in Fig. 6 were measured at the color location where we observed the largest change between the near- and far-fovea thresholds. For both subjects, when the central point fell in the far fovea, sensitivity decreased by a scale factor of 1.74. At the other two color locations sensitivity decreased by a scale factor of 1.3. Constraining the near- and far-fovea ellipsoids to be scaled versions of each other did not substantially increase the error, **E**. When each ellipsoid was fitted independently, the range of errors for the 12 ellipsoids was 0.112–0.221. When the ellipsoids were constrained to be scaled versions of each other, the error range was 0.113–0.252. The largest increase in **E** for any ellipsoid was 0.034.

Effect of Distractor Grid Size

We measured thresholds using a 7 × 7 distractor grid, which increased the expected number of objects but left the separation between the target item and its nearest distractor item unchanged. With the larger distractor grid the expected number of objects on each trial increased from 5 (variance equals 2) to 25 (variance equals 12). We observed no substantial change in the estimated ellipsoid when we increased the distractor grid size. In Fig. 7 we present data from two observers for each of the distractor grid sizes. We plot thresholds measured in the red–green plane.

We were somewhat surprised that increasing the expected number of distractor items had no measurable effect on these thresholds. These results were quite different from measurements that we made in a series of pilot studies. In those experiments we did not control for the spatial separation betweeen the target item and the nearest distractor item. When we increased the number of distractor items by increasing the probability of presenting a distractor item at each grid point, the threshold decreased. The spatial distribution of the distractor items relative to the target item is probably a more important determinant of the distractors' effect on sensitivity than the number of distractors.

Comparison with Color-Matching Ellipsoids

The classic color-discrimination ellipsoids derived by Brown and MacAdam[4] were estimated by approximating the dispersion of a set of color matches by a trivariate normal distribution. The set of points 1 standard deviation from the mean of the trivariate normal forms an ellipsoidal surface. How do the ellipsoids that we report compare with the ellipsoids estimated using the Brown–MacAdam procedure?

Observer TG performed a series of color matches to three different test fields. The test-field color coordinates were the same as the color coordinates of the distractor items in our discrimination task. A pair of 1-deg squares was placed side by side on an otherwise dark monitor. The square on the left was held constant at one of the distractor color coordinates. The subject adjusted the color appearance of the square on the right until it appeared to match the square on the left. Following Wyszecki and Fielder,[18] the observer made 30 color matches at each color coordinate. These conditions were very similar to those used by Brown and MacAdam.[4,5] To find the color-matching ellipsoid, we computed the 3 × 3 covariance matrix of the 30 × 3 matrix of color-match settings. The parameters of the best-fitting trivariate normal are determined by the mean of the matches and the inverse of the covariance matrix.[6]

In our discrimination task we made more threshold measurements in the red–green receptor plane than in any other plane. The strongest comparison that we can make between

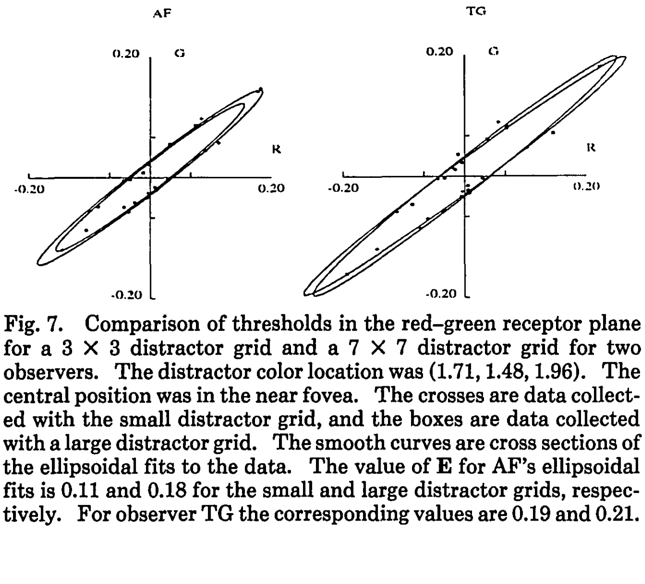

Fig. 7. Comparison of thresholds in the red–green receptor plane for a 3 × 3 distractor grid and a 7 × 7 distractor grid for two observers. The distractor color location was (1.71, 1.48, 1.96). The central position was in the near fovea. The crosses are data collected with the small distractor grid, and the boxes are data collected with a large distractor grid. The smooth curves are cross sections of the ellipsoidal fits to the data. The value of **E** for AF's ellipsoidal fits is 0.11 and 0.18 for the small and large distractor grids, respectively. For observer TG the corresponding values are 0.19 and 0.21.

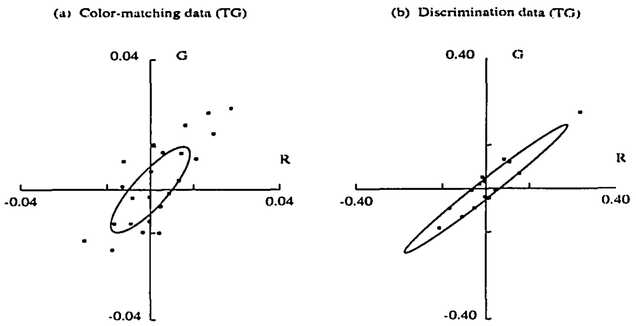

Fig. 8. Color-matching and discrimination data for observer TG. (a) Color matches are projected onto the red–green receptor plane at color location (1.71, 1.48, 1.96); the smooth curve is the ellipse at one standard deviation for the trivariate normal fit to the data. (b) Threshold discriminability is shown for the near fovea, distractor grid 3 × 3, color location (1.71, 1.48, 1.96).

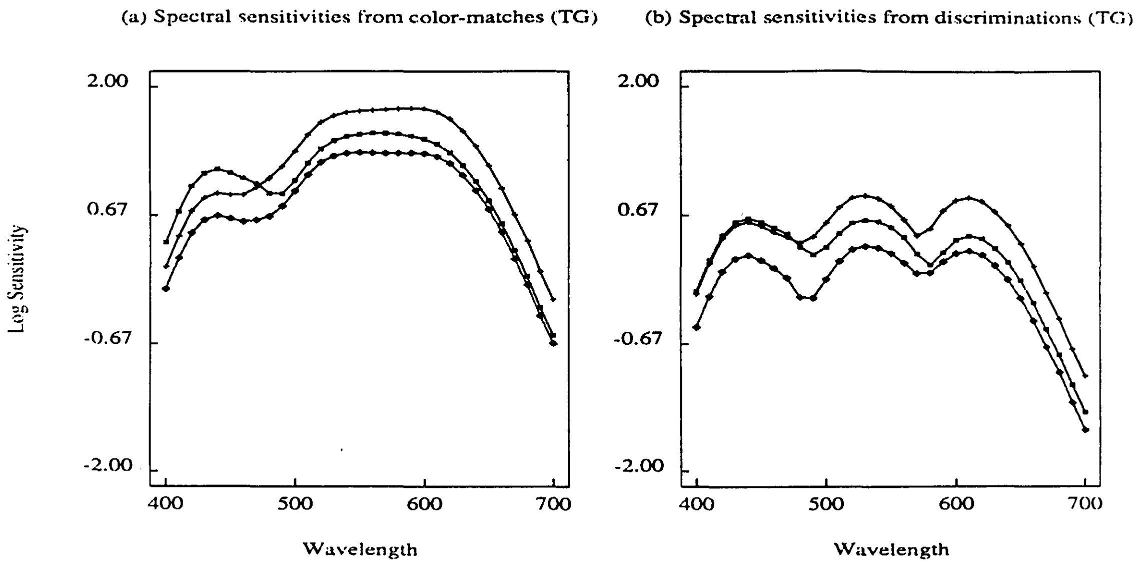

Fig. 9. Spectral-sensitivity comparison for observer TG at three different locations in color space: cross, (1.71, 1.48, 1.96); box, (3.10, 2.65, 1.84); diamond, (4.81, 4.13, 3.80). (a) The spectral-sensitivity curves derived from the ellipsoids estimated from the color-matching variability. (b) The spectral-sensitivity curves derived from the ellipsoids estimated in our threshold discrimination task. These curves are near fovea, distractor grid size 3 × 3.

the thresholds measured in the discrimination task and the color-matching task is in the red–green plane. Figure 8(a) shows the color matches projected onto the red–green receptor plane along with the cross section of the color-matching ellipsoid. This color-matching ellipse can be compared with the discrimination ellipse that is estimated in the discrimination task [Fig. 8(b)].

The color-matching ellipse is approximately seven times smaller than the discrimination ellipse, indicating that the observer is more sensitive to color differences in the color-matching task than in the discrimination task. Further, the ellipses are oriented in slightly different directions. One way to evaluate the significance of these differences in the full ellipsoids is to compare the derived spectral-sensitivity curves. We plot the three spectral-sensitivity curves derived from our color-matching ellipsoids [Fig. 9(a)] and three derived from our discrimination ellipsoids [Fig. 9(b)].

The difference in the observer's overall sensitivity between the two tasks is shown by the upward shift of the color-matching spectral sensitivities compared with the discrimination spectral sensitivities. Beyond the overall shift in sensitivity, there are two obvious differences in the shapes of the spectral sensitivity curves. First, the data from the color-matching task do not show the three lobes that are characteristic of our discrimination data and the discrimination data reported elsewhere.[12,16] Rather, the two long-wavelength lobes have merged into a single lobe. Second, the relative sensitivity of the short-wavelength lobe is lower in the color-matching task than the discrimination task. In the color-matching task the observer bases his judgment largely on the presence or absence of a border between the two sides of the field. The relative ineffectiveness of the short-wavelength receptors in the color-matching task is consistent with the observation that these receptors are present only at widely spaced retinal points[19] and make a relatively small contribution to the detection of fine borders.[20]

CONCLUSIONS

We summarize our results with four points. First, the data from the complex discrimination task are as well summarized by the ellipsoidal form, as are data from detection tasks. Second, even within the fovea, small differences in the target item position lead to differences in the discrimination ellipsoid. For our conditions we observed changes in sensitivity of 30–70% when we compare targets that fall in the central 1 deg of the fovea with targets that fall from 1.0 to 1.5 deg around the fixation point. Third, increasing the distractor grid size but holding the spatial statistics of the distractors constant did not substantially alter the parameters of the best-fitting discrimination ellipsoid. Fourth, we compared the color-matching ellipsoids to discrimination ellipsoids. A d' of 1 in the discrimination experiment corresponded to between 4 and 7 standard deviations of the estimated trivariate normal in the color-matching experiment. The observer's spectral sensitivity, estimated from the ellipsoids in these two tasks, was substantially different.

APPENDIX A

This appendix reports the parameters of the twelve ellipsoids estimated in the discrimination task (Tables 1 and 2) and three ellipsoids estimated in the color-matching task (Table 3). The parameters are given in matrix form, **Q**, following the convention in Poirson *et al.*[12]

Table 1. *Q* Estimated from Discrimination Task at Distractor Color Location (1.71, 1.48, 1.96)

Target	Distractor Grid Size 3 × 3						Distractor Grid Size 7 × 7					
	Near Fovea			Far Fovea			Near Fovea			Far Fovea		
Obs. AF	722.24	−907.38	82.99	230.85	−290.76	37.70	949.84	−1181.10	144.28	180.06	−205.88	−42.92
	−907.38	1187.47	−59.44	−290.76	385.16	−32.30	−1181.10	1535.36	−124.19	−205.88	257.64	69.23
	82.99	−59.44	51.85	37.70	−32.30	18.31	144.28	−124.19	67.64	−42.92	69.23	28.49
Obs. TG	557.78	−698.74	51.05	145.38	−185.65	17.90	609.21	−817.77	67.54	154.81	−197.16	18.64
	−698.74	901.00	−66.81	−185.65	245.93	−12.19	−817.77	1123.68	−94.17	−197.16	264.34	−6.74
	51.05	−66.81	35.29	17.90	−12.19	15.07	67.54	−94.17	36.08	18.64	−6.74	24.08

Table 2. *Q* Estimated from Discrimination Task at Two Distractor Color Locations[a]

Color Location (3.10, 2.65, 1.84)						Color Location (4.81, 4.13, 3.80)					
Near Fovea			Far Fovea			Near Fovea			Far Fovea		
99.32	−137.17	24.93	43.22	−55.51	26.61	41.67	−51.66	11.82	14.55	−18.42	−0.32
−137.17	198.06	−23.71	−55.51	76.86	−39.48	−51.66	68.26	−15.32	−18.42	25.10	−3.15
24.93	−23.71	39.14	26.61	−39.48	31.27	11.82	−15.32	7.25	−0.32	−3.15	7.09

[a] Distractor grid size 3 × 3 for observer TG.

Table 3. *Q* Estimated from Color-Matching Task at Three Color Locations[a]

Color Locations								
(1.71, 1.48, 1.96)			(3.10, 2.65, 1.48)			(4.81, 4.13, 3.80)		
21839.23	−16792.51	591.42	4831.43	−3156.76	121.37	2683.36	−2209.74	24.86
−16792.51	18661.65	−355.60	−3156.76	3930.40	−39.81	−2209.74	2673.90	−43.65
591.72	−355.60	112.17	121.37	−39.81	244.46	24.86	−43.65	44.47

[a] Observer TG.

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