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The contribution of color to visual memory in normal and color deficient observers

Karl R. Gegenfurtner, Felix A. Wichmann and Lindsay T. Sharpe

Abstract

We used a recognition memory paradigm to assess the influence of color information on visual memory for color images of natural scenes. During the presentation phase 48 images of natural scenes were presented on a CRT for exposure durations between 50 and 1000 msec followed by a random noise mask. Half of the images were presented in color and half in black & white. In the subsequent query phase the same 48 images were intermixed with 48 new images and the subjects had to indicate which of the images they had already seen during the presentation phase. We found that performance increased with exposure duration. However, independent of exposure duration subjects performed 5-10% better for colored than for black & white images, even for exposure durations as short as 50 msec. This effect cannot be due to contrast differences in the images since a second experiment showed little effect of contrast once the images were suprathreshold. Further experiments showed that performance worsened when images were presented in color and tested in black & white, or vice versa. Performance was not impaired for a comparison group of 31 color deficient observers (17 protanopes and 14 deuteranopes), whose recognition performance was also better for colored than for black & white images. We conclude that color information plays an important role in the early and fast processing of visual images. Both sensory and cognitive factors seem to contribute to the superior recognition of color images. Finally, color-deficient observers appear to be able to compensate for their reduced chromatic information range when viewing and analyzing complex scenes.

Felix Wichmann is at the Department of Experimental Psychology, Oxford University, South Parks Road, Oxford OX1 3UD, UK. Ted Sharpe is at the Forschungsstelle für Experimentelle Ophthalmologie, Universität Tübingen Röntgenweg 11, D-72076 Tübingen, Germany. Part of this work was presented at the annual meeting of ARVO (Wichmann & Gegenfurtner, 1995) and at ECVF (Gegenfurtner et al., 1995). We thank Jeremy Nathans (The Johns Hopkins University School of Medicine) for performing the molecular genetic analysis of our dichromatic observers. Supported by DFG (Bonn) Grants SFB 325 (B13) and by the Heisenberg-Programme.

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1. Introduction

The early stages of color perception, the absorption of light of different wavelength by the cones and the subsequent processing in color opponent channels, have been extensively researched and are well understood at the psychophysical, physiological and molecular genetical level (for reviews, see Stockman, MacLeod & Johnson, 1993; Kaplan, Lee & Shapley, 1990; Nathans, Merbs, Sung, Weitz & Yang, 1992). The later stages, the role of chromatic information in higher level vision and visual cognition, on the other hand, are not yet clear. Most research in the recent past has been concerned with the way visual perception fails when color is the only information available. The results of this line of inquiry, though initially promising (Livingstone & Hubel, 1987), have turned out to be complex and difficult to interpret (Shapley, 1990). In contrast, very few researchers have considered what chromatic information adds to already existing luminance information. Yet this question is particularly interesting because at least the red-green color-opponent system is believed to have developed subsequent to and parasitic upon the luminance-sensitive visual system (Mollon, 1989). Left largely unconsidered is what practical - and hence evolutionary advantageous - purposes color vision serves over and above the visual systems ability of discriminate luminances. In this paper we will address two aspects of this problem. First, whether one of the advantages of having additional chromatic information, versus luminance information alone, may manifest itself in visual recognition memory. Second, whether a fully intact red-green opponent system is necessary for any advantage to manifest itself.

The difference in appearance between color and black & white photographs is quite obvious. Thus it might initially appear that investigating the possible advantages of color vision is a trivial pursuit. However, the beauty of color vision in itself is not a “practical function” and thus rather unlikely to be of evolutionary significance. Second, and more importantly, about 8% of the male population are at least partially color-blind, but many of them do not become aware of their deficiency until formally tested. Finally, the very few studies on the effect of color in visual cognition so far conducted have failed to yield conclusive results.

1.1. Color in Visual Cognition

Most of the previous studies investigating the role of color in visual cognition have looked at object recognition. Ostergaard & Davidoff (1985) found a significant effect of color on object naming latencies provided that

objects were presented in their natural color. Biederman & Ju (1988), however, failed to find such a beneficial effect of color information when measuring naming and verification latencies during object recognition. It is important to note, however, that Ostergaard & Davidoff used color versus black & white photographs of objects whereas Biederman & Ju compared color photographs with line drawings. Moreover, as pointed out by Wurm et al. (1993), neither of the investigators matched the luminance distributions of their color and non-color images, thereby further complicating any attempt to explain the discrepancies between their results. Wurm et al. did match the luminance of their color and grey-level images pixel by pixel and found that the additional chromatic information not only decreased the reaction time during object recognition but also increased the recognition accuracy. The advantage for colored images in their experiment was independent of the diagnosticity of the color of an object, pointing towards a sensory rather than a cognitive explanation.

1.2. Color in Image Segmentation

All above mentioned studies presented the to-be-detected or recognized object in isolation against a uniform background. A possible evolutionary advantage for color vision over luminance based vision only may lie, however, in segmenting objects from textured backgrounds (Walls, 1942; Polyak, 1957). This hypothesis is, albeit only indirectly, supported by the existence of several machine-vision algorithms that very successfully combine chromatic and luminance information to derive a meaningfully segmented representation of the visual scene (Healey, 1989, 1992; Lee, 1990; Perez & Koch, 1994). Thus it might be argued that the equivocal results obtained by Ostergaard & Davidoff, Biederman & Ju and Wurm et al. might at least be partially owing to their chosen experimental paradigm, rather than reflecting a lack of, or only a minimal influence of, color on visual cognition. In order to circumvent this possible limitation, we chose images of natural scenes as our stimuli and used a recognition memory paradigm for our experiments.

2. Experiment 1: Color versus Black & White

2.1. Method

Procedure. The first experiment consisted of two phases: A presentation phase, in which subjects were sequentially presented a set of 48 images of the kind shown in Fig. 1, and a query phase in which subject's



Figure 1: Example images from the four different categories. The top left image is from category 1, “green” landscapes of fields and forests around Tübingen; the top right image is from category 2, flowers; the bottom left from category 3, rock formations; and the bottom right from category 4, man-made objects. All the landscapes were quite similar in color and shape. Flowers differed widely in color, little in shape. Rock formations were similar in color, but had large variations in shape. The man-made objects had large variations both in color and shape.

memory for the images was tested. First each image was presented for 50 to 1000 msec, with a 7-second interval between successive images. In the subsequent query phase the same 48 images were randomly intermixed with 48 new images, and the observers’ task was to indicate whether they had already seen an image during the presentation phase. The query phase was self-paced; each image was presented until the subject reached a decision and gave a response. The response consisted of a yes-no answer and a confidence rating, on a scale from 3 (absolutely certain) to 0 (undecided).

Stimuli. The images were chosen from four different categories: green landscapes with fields and trees, like the one shown in the upper left of Fig. 1; flowers (Fig. 1, upper right); rock formations (Fig. 1, lower left), and man-made objects (Fig. 1, lower right).

Images were not formally screened for category membership, but when subjects were asked they were able to assign the images to the different categories without difficulty. The non-formal screening procedure was used simply because there is no formal – working – theory of similarity or category membership (see e.g. Snodgrass &

McCullough, 1986; Barsalou, 1989 or Herrnstein, 1985). The picture selection process was similar to that described by Potter (Potter & Levy, 1969; Potter, 1976). Pilot studies ensured that, overall, the chosen images were recognized at approximately 80% correct for the longest viewing durations employed (to avoid either floor or ceiling effects). The critical differences between the categories are that the images in category 1 (landscapes) are all quite similar in both color (green) and texture (grass, leaves), those in category 2 (flowers) differ greatly in color and very little in texture, those in category 3 (rock formations) differ greatly in shape but very little in color, and, finally, those in category 4 (man-made objects) differ widely in both color and shape.

For each subject in all the experiments half of the 48 images were randomly chosen to be presented in color, the other half in black & white. The luminance component of the images was identical under both conditions, and the space averaged mean luminance was about 35 cd/m². Every image was immediately followed by a mask consisting of pixel blocks randomly chosen from color space, with the restriction that for the black & white images the mask was made up of black & white

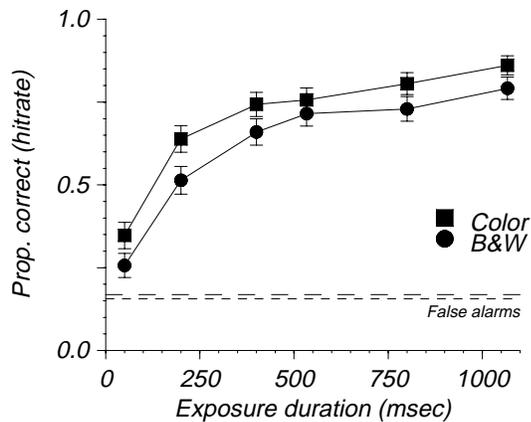


Figure 2: Proportion of correctly recognized images (hit rate) as a function of exposure duration of the images during the presentation phase. Filled squares indicate images presented in color, filled circles indicate images presented in black & white. The horizontal dashed lines specify the rate of false alarms.

instead of colored blocks. Images that were presented in color during the presentation phase were always presented in color during the query phase, and likewise for black & white.

Experiments were run on a Silicon Graphics Indigo II workstation with a 24 bit framebuffer. There were 60 refresh cycles per second. Images were presented for 3, 12, 24, 32, 48 and 64 frames, resulting in presentation durations of 50, 200, 400, 533, 800 and 1067 msec. The image presentation was ended by switching the hardware lookup table to a gray of mean luminance, while the mask was drawn into the frame buffer. The interval between the termination of the stimulus and the onset of the mask was 16.7 msec. The mask was presented for 200 msec, followed by another uniform field of gray at mean luminance.

Subjects. Young (20-25 years old) male and female students of the University of Tübingen served as subjects in the first three experiments. They were paid for their participation. Thirty-six subjects participated in experiment 1.

2.2. Results

Fig. 2 shows the results of experiment 1. Exposure duration of the images during the presentation phase is shown

on the x-axis, and the rate of correctly recognizing an image, the hit rate, is plotted on the y-axis. Each data point is based on 144 observations, 4 per subject. False alarm rates are shown by the dashed lines at the bottom of the graph. There was no difference in the false alarm rate between luminance and color distractors. Since no exposure durations could be assigned to the distractors (by definition they were not presented during the presentation phase), only hit rates will be presented here. Table 1 shows the results of an analysis of variance. Significant main effects were observed for exposure duration, for image category and for color versus black & white. A weak interaction was present only for exposure duration and category.

The effect of exposure duration is typical for transfer to short term memory (Gegenfurtner & Sperling, 1993). Performance increases rapidly at first, then reaches an asymptotic level at around 500 msec. Further, there were significant differences between image categories. Subjects found the man-made objects easier to recognize (mean correct 86.4%) than rock formations (mean correct 73.5%), flowers (mean correct 68.1%) or green landscapes (mean correct 67.8%). The interaction between exposure duration and image category was mostly owing to the better performance for category 4 (man-made objects) than for the other categories at the very short presentations. The important issue from the point of this paper is the effect of color versus black & white presentation. The squares forming the top curve show performance for the colored images, the circles forming the bottom curve show performance for black & white images. There is a difference of about 8% between the two conditions and this difference is independent of exposure duration. The two curves are only vertically shifted. The performance difference is already present for 50 msec exposures and it remains constant up to exposure durations of 1 sec (the longest tested).

Thus there is a clear effect of color on recognition memory. Although a performance improvement of 8% might appear rather small, it has to be evaluated within the context of our image selection: they were chosen to be difficult to recognize in order to avoid ceiling effects. This is reminiscent of the debate whether images or words can be remembered better: it boils down the experimenter's choice of distractors during recall (see Carmichael et al., 1932; Daniel, 1972; Snodgrass & McCullough, 1986; Standing, 1973). It is interesting to speculate whether there would be any other image manipulation that could possibly increase the level of asymptotic performance in such a significant fashion.

Our expectation when we ran these experiments was that the influence of color on recognition memory would dif-

Table 1: Analysis of variance for normal observers

SOURCE	SS	df	MS	F	p
Image category	9.4375	3	3.1458	17.030	< 0.001***
Exposure duration	52.2407	5	10.4481	56.826	< 0.001***
category x duration	4.7639	15	0.3176	1.819	0.0293*
Presentation color	2.8356	1	2.8356	17.521	< 0.001***
category x color	0.3449	3	0.1150	0.659	0.5792
duration x color	0.2685	5	0.0537	0.261	0.9337
category x duration x color	2.5509	15	0.1701	0.981	0.4741

fer for the different image categories. This is because in categories 2 (flowers) and 4 (man-made objects) there was a large-scale variation in color between the different images, whereas in categories 1 (landscapes) and 3 (rock formations) there was not. However, the results of experiment 1 revealed no interactions between image category and presentation mode, nor between presentation mode and exposure duration. Fig. 3 shows the performance for each category for color (left bar) and black & white (right bar). The open bars show the hit rates, the filled bars false alarm rates. As previously mentioned, there are large performance differences between the different categories. The green landscapes (category 1) were most difficult, flowers (category 2) and rock formations (category 3) intermediate, and the man-made objects (category 4) were easiest. But, interestingly, performance is better for color images in all the four categories. No interaction was found between image category and presentation condition (see Table 1, $p = 0.58$). This might indicate that color images do not simply have more information than their black & white counterparts: for the landscapes and for the rock formations the color information appears, at least superficially, rather redundant, whereas it appears highly important for the flower images. Nevertheless, all categories benefitted similarly from the added chromatic information.

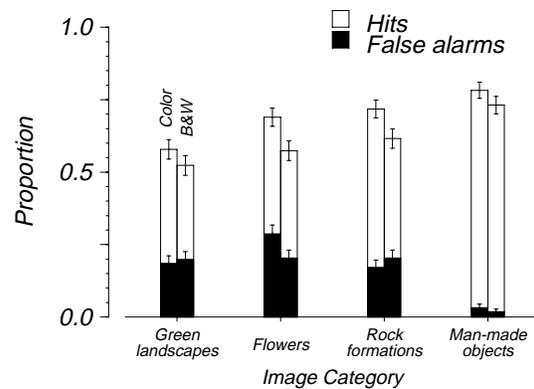


Figure 3: Proportion of hits (open bars) and false alarms (solid bars) for each image category. The left bar of each pair is for images presented in color, the right one for images presented in black & white.

3. Experiment 2: Effects of Contrast

One potential problem with the comparison between colored and black & white images is the specification of image contrast. Contrast is well-defined for luminance variations. The contrast of each single pixel is specified as the “Weber”-contrast $C = \Delta L/L$, where L is the luminance at that pixel and ΔL is the difference between L and the space averaged luminance of the whole image. For such achromatic or black & white luminance variations, the contrasts for all three types of photoreceptors are equal at each pixel. Contrast of the whole image can then be defined as the maximum of all pixel contrasts. For color images the situation is more difficult, since at each pixel the contrasts of the three photoreceptors will typically be different. One could use some weighted sum of the longwave (L-), middlewave (M-), and shortwave (S-) sensitive cone contrasts, but there is no unique, or inherently superior, procedure for choosing the weights (Lennie & D’Zmura, 1988). If recognition rate depends on image contrast, then it is possible that the difference between color and black & white could simply be owing to an increased image contrast in the color images. We therefore varied image contrast in experiment 2.

3.1. Methods

All methods were identical to the ones used in experiment 1, except that exposure duration was constant at 1 sec in experiment 2, and six different image contrasts were used: 5%, 10%, 20%, 40%, 70% and 100%. These contrasts were specified as a percentage relative to the original image. Contrast reductions were achieved by scaling the color difference of each pixel relative to the mean color. The same procedure was applied for black & white and color images, so that at each contrast level the luminance components of the colored and black & white images were identical. Exposure duration was constant at 500 msec. Thirty-four new subjects participated in experiment 2.

3.2. Results

Results are shown in Fig. 4: contrast is plotted on the x-axis against hit rate on the y-axis. Again there is an advantage for color over the black & white images, except for the very lowest contrasts where the images were hardly visible. What is important to note is that at contrast levels above 40% recognition memory performance is independent of contrast. Thus contrast effects are very unlikely to account for the difference in recognition memory performance between color and black & white images in experiments 1 and 2. This also excludes

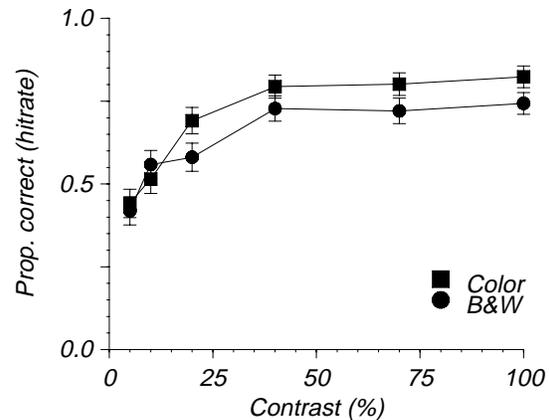


Figure 4: Proportion of correctly recognized images (hit rate) as a function of image contrast during the presentation phase. Contrast is defined as the maximum contrast of an individual pixel with respect to the full-contrast image. Filled squares indicate images presented in color, filled circles indicate images presented in black & white.

the possibility that the minimal contrast variations unavoidably arising from chromatic aberration within natural images account for the difference in recognition performance between color and black & white images (Marimont & Wandell, 1994).

4. Experiment 3: Sensory versus Cognitive Facilitation

Contrast has been ruled out as a possible candidate to explain the superior recognition for color images. There are two other obvious candidates. First, as already mentioned in the introduction, it is possible that color helps the visual system to process images faster, for example by achieving faster segmentation into separate objects. We will refer to this possible advantage as sensory facilitation. Second, it is likely that color is part of the memory representation and thus allows more features to be associated with each object in memory. We will refer to this possible advantage as cognitive facilitation. In Experiment 3 we tried to determine if one of these factors by itself could explain the performance differences.

4.1. Methods

The methods were the same as those used in experiment 2, save that all images could be tested now in color or in black & white, regardless of how they were originally presented. Exposure duration was again constant at 1 sec. Only three different levels of contrast were used, 10%, 50% and 100%. Thirty-one new subjects participated in experiment 3.

4.2. Results

An analysis of variance revealed main effects of image category, contrast, and presentation mode. In addition, there was a strong and significant interaction between presentation mode and query mode ($F_{1,30} = 0.209$, $p < 0.01$). Fig. 5 shows this interaction effect. Presentation color mode is plotted on the x-axis, black & white to the left and color to the right. Query color mode is shown by the two different symbols, squares for color and circles for the black & white query. Performance for images presented in color was much worse when the images were queried in black & white, and *vice versa* performance for images presented in black & white was worse when the same images were queried in color. But as in the above experiments, there was a distinct advantage for color presentations, regardless of whether they were queried in color or black & white ($F_{1,30} = 4.576$, $p < 0.05$).

4.3. Discussion

If sensory facilitation alone were responsible for the superior recognition memory for color images, then the facilitation should be independent of query color and both curves should fall on top of each other. This is clearly not the case and we conclude that sensory facilitation alone cannot account for the performance difference. Conversely, as mentioned in the results section of experiment 1, it appears unlikely that cognitive facilitation alone is responsible for our results since the color advantage did not significantly depend on image category. This would be expected if the memory advantage were purely cognitive since, for flowers, color appears to be much more integral to identification than for similarly colored green landscapes. Further, even if the increased recognition performance was purely cognitive, it is important to note that the extraction of chromatic information is fast. Indeed, its beneficial influence is already fully present at presentation times of 50 msec. We will come back to this fact in the general discussion.

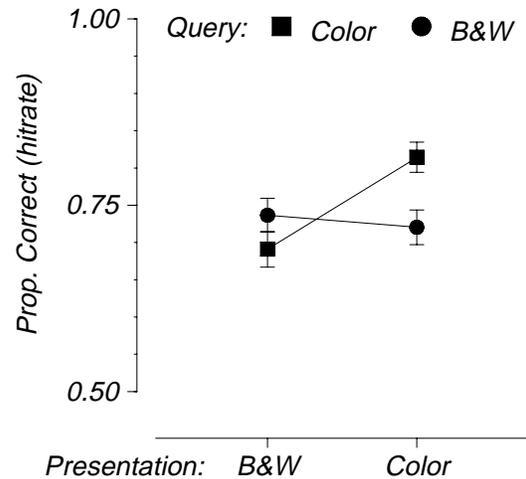


Figure 5: Results of experiment 3. The x-axis plots whether images were presented in black & white (left) or color (right). The y-axis plots the proportion of correctly recognized images (hit rate) for images queried in color (filled squares) and black & white (filled circles).

5. Experiment 4: Color Deficient Observers

In the fourth and final experiment we addressed the issue of color-deficiency. As previously stated, many color-deficient persons only become aware of their deficiency when formally tested. Numerous screening tests for color-deficiency have been devised in the past, and they are all based on the principle of restricting color information to one or two subspaces of the three-dimensional color space spanned by all three cone types. We are not aware of any experiments that have investigated how detrimental color-deficiency is for the perception of natural scenes, in which full three-dimensional color information is present. Only attempts have been made to simulate for normal observers the perceptions of partially color blind observers when viewing complex scenes (for two recent examples, see Usui & Nakauchi, 1995; Vienot, Brettel, Ott, Ben M'Barek & Mollon, 1995).

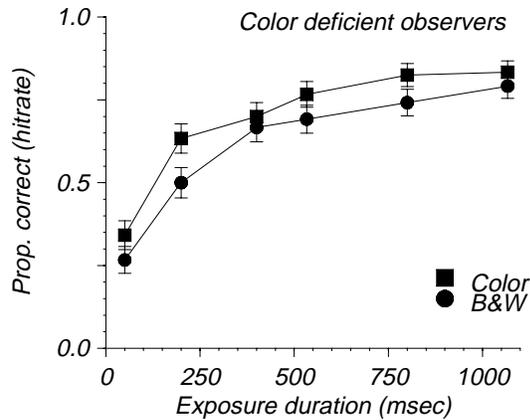


Figure 6: Proportion of correctly recognized images (hit rate) as a function of exposure duration of the images during the presentation phase for 31 color-deficient observers. Filled squares indicate images presented in color, filled circles indicate images presented in black & white.

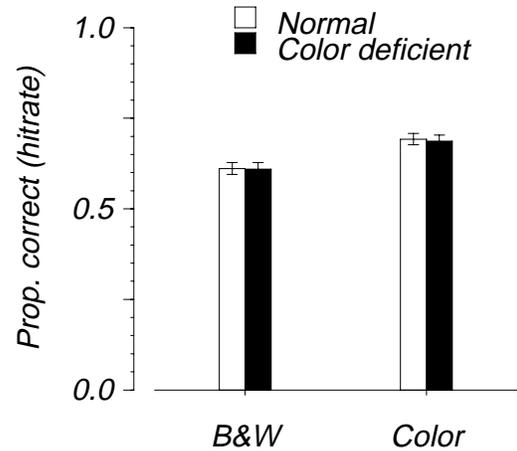


Figure 7: Comparison of the proportion of correctly recognized images (hit rate) for normal (open bars) and color-deficient (filled bars) observers. The left bar of each pair indicates performance for images presented in black & white, the right bar performance for images presented in color.

5.1. Methods

The methods were the same as those used in experiment 1, save that the subjects in experiment 4 were thirty-one color-deficient dichromats. They were recruited from a large database at the University of Freiburg i. Br. established for a project correlating red-green color-blind genotypes with phenotypes. The color-deficient subjects ranged in age from 15 to 55 years (mean 22 years). All were diagnosed as protanopic or deuteranopic by standard color vision tests, which included the Ishihara pseudoisochromatic plates and the Nagel III anomaloscope. Dichromacy was confirmed by foveal (2 deg) heterochromatic brightness curves measured as a function of wavelength by the minimal-flicker (25 Hz) method. Southern blotting analysis, performed by Dr. J. Nathans (The Johns Hopkins University, Baltimore), indicated that 6 of the protanopes and 8 of the deuteranopes had a single opsin gene in the red-green tandem array on the X-chromosome; the remaining 11 protanopes and 6 deuteranopes had two or more opsin genes. In the single-gene dichromats, exons 2 to 5 were PCR amplified and sequenced on both strands. This revealed that the 8 single-gene deuteranopes had a single normal red (or long-wave sensitive) pigment gene with the serine polymorphic variant R(ser^{180}); and that the six protanopes had a

single 5' red - 3' green-hybrid pigment gene: one with a R1G2 gene, one with a R2G3 gene, three with a R3G4(ser^{180}) gene and one with a R4G5(ser^{180}) gene (see Nathans et al., 1986a,b). Only one of the dichromats was female (a multiple gene deuteranope).

5.2. Results

In Figure 6 exposure duration is plotted versus hit rate for color images and for black & white images. Interestingly, the curves are virtually identical to the ones obtained for normal observers in experiment 1. Again there is an approximately 8% difference in performance in favor of the color images, and, again, this difference is fairly constant over different exposure durations. Table 2 shows the results of an analysis of variance. The same main effects as in experiment 1 were observed, but the interaction between exposure duration and image category was not significant. This indicates that processing of both types of images is quite similar.

Fig. 7 compares overall performance of the color-deficient observers with that of the normal observers from experiment 1. There is no difference whatsoever between the two groups, neither for color, nor for black & white images. There was also no significant difference between

Table 2: Analysis of variance for color deficient observers

SOURCE	SS	df	MS	F	p
Image category	6.5743	3	2.1914	9.212	< 0.001***
Exposure duration	42.7285	5	8.5457	52.356	< 0.001***
category x duration	1.5632	15	0.1042	0.508	0.9366
Presentation color	1.9507	1	1.9507	15.663	< 0.001***
category x color	0.1521	3	0.0507	0.261	0.8530
duration x color	0.3785	5	0.0757	0.449	0.8133
category x duration x color	2.8354	15	0.1890	1.138	0.3195

protanopes and deuteranopes in the task; nor between single-gene and multiple-gene dichromats.

6. Discussion

Our series of experiments has established that color plays an important role in recognition memory for natural scenes. Performance for color images is superior to performance for black & white images at all the exposure durations tested. The effect is at least partly due to cognitive facilitation, the enriched memory representation for color images. However, since the effect is already fully developed at 50 msec and constant across image categories it is not unreasonable to suggest that faster image segmentation – sensory facilitation – might have contributed to the superior recognition performance as well as cognitive facilitation.

6.1. Models of information flow

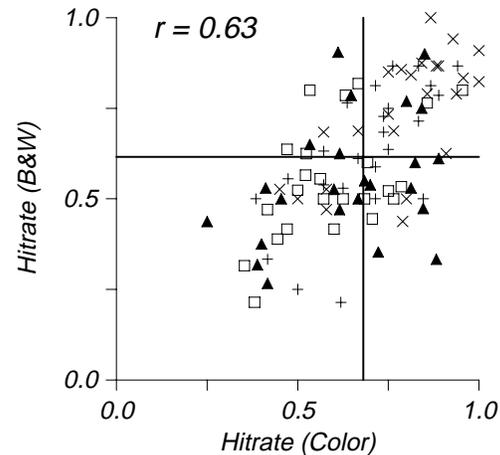
The most astounding feature of our results is certainly that the two curves for hit rate, for color and for black & white, are nearly perfect copies of one another, with the color curve shifted vertically by about 8%. The shape of the curve is quite similar to the information transfer curves typically observed when sensory (or iconic) memory is converted into a more durable form of storage, short-term memory (Gegenfurtner & Sperling, 1993). This result also argues in support of a low-level or sensory explanation for the color superiority, assuming that any benefits occurring at very short (50 msec) exposures would have to take place at a rather early level. If

color can only help through cognitive facilitation, then the features coding color would have to be fully processed within 50 msec. Within that time period, absolute performance is still close to chance; so this implies that color is being processed faster than most other features, which contradicts physiological observations that processing of color is slower, if anything, in the visual cortex (Munk et al., 1995). Unfortunately this question is not easy to resolve, since presentation times shorter than 50 msec cannot be used within the present paradigm. Performance would simply be too low.

6.2. How color-blind is red-green-blind?

We found absolutely no difference in performance between normal (trichromatic) and dichromatic observers in our experiments. This shows, on the one hand, quite nicely that dichromats are far from being color-blind. In fact, the ones who participated in our experiment were red-green color-blind, which means that they have poor color discrimination in the red-to-green part of the spectrum. Thus the blue-yellow color opponent system alone seems to be quite capable of supporting performance in our recognition memory task. On the other hand, this leaves the puzzle of the practical purpose of color vision, set out in the introduction, at least partially unresolved. Yes, color does facilitate recognition memory. But, it appears, dichromacy is perfectly capable of supporting both the sensory and cognitive facilitation observed in our study. What advantage, then, is provided by the third chromatic dimension?

Figure 8: Recognition performance for the 98 images used in this study. The x-axis plots the hit rate for a particular image when it was presented in color. The y-axis plots the hit rate of the same image when it was presented in black & white. The heavy horizontal and vertical lines indicate the average performance under those two conditions. Different symbols indicate the four different image categories: green landscapes (open squares), flowers (filled triangles), rock formations (+’s), and man-made objects (x’s). The coefficients of correlation between color and black & white performance were 0.59, 0.39, 0.67, and 0.68 for the four different categories, respectively, and 0.63 for the overall sample.



When considering red-green color-blindness, it must be remembered that many of the afflicted are only dichromatic for small viewing fields, such as those typically employed by the Nagel anomaloscope. For larger fields, they become partially trichromatic and are able to make red-green colour discriminations. This is the so-called ‘large-field trichromacy’, first observed by Nagel (1905). The basis of this enhanced color discrimination is unclear. It depends not upon field size (larger fields are better than small ones), but also upon transient stimulation (flickering fields are better than steady ones). The viewing conditions in our experiments, may have been such that some of the dichromats could have profited from improved discrimination owing to large-field trichromacy. However, even with large-field trichromacy operating, they would still have greatly reduced red-green color discrimination compared with normals (i.e. they would behave as extreme anomalous trichromats rather than as normal trichromats). Yet their performance on the recognition memory task was equal to that of normals.

6.3. What do we remember well?

One question that immediately springs to mind is whether there are any particular features we can recognize faster or better than others. To answer that question we looked at performance as a function of the image. First of all, we determined for which images color information is important; that is, for which images is the dif-

ference in performance between color and black & white largest. Figure 8 plots hit rates for color on the x-axis against hit rate for black & white presentations on the y-axis. Only data from experiment 1 were used for comparison. The high correlation of 0.63 across all four categories indicates that about 40% of the whole variance in recognition performance can be attributed to the luminance components of the image. It is interesting to note, however, that a difference between categories is apparent here. The correlations by categories were 0.59 for the green landscapes (category 1), 0.67 for the rock formations (category 2), 0.68 for the man-made objects (category 4), but only 0.39 for the flowers (category 2). Thus color does seem to play a larger role for the flower images than for the other images, but only in determining which images can be better remembered.

We analyzed individual images with respect to their mean (average) color and variance of colors, but no systematic relationship was found between any of these properties and recognition performance for the images. The question of which aspects of the color support easy recognition will have to be answered with stimuli which can be manipulated more easily. Certainly color as a whole makes an important contribution.

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