The Contributions of Color to Recognition Memory for Natural Scenes

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The authors used a recognition memory paradigm to assess the influence of color information on visual memory for images of natural scenes. Subjects performed 5%–10% better for colored than for black-and-white images independent of exposure duration. Experiment 2 indicated little influence of contrast once the images were suprathreshold, and Experiment 3 revealed that performance worsened when images were presented in color and tested in black and white, or vice versa, leading to the conclusion that the surface property color is part of the memory representation. Experiments 4 and 5 exclude the possibility that the superior recognition memory for colored images results solely from attentional factors or saliency. Finally, the recognition memory advantage disappears for falsely colored images of natural scenes: The improvement in recognition memory depends on the color congruence of presented images with learned knowledge about the color gamut found within natural scenes. The results can be accounted for within a multiple memory systems framework.

Introduction

"A picture is worth a thousand words"—this phrase has inspired numerous investigations of the properties of human visual and verbal memory. It has become clear that there is enormous memory capacity for storing pictures of objects and scenes (Nickerson, 1965; Shepard, 1967; Standing, 1973). However, it has proven very difficult to quantify and compare the contributions of pictorial and verbal information on memory performance. In addition, al-though the early sensory processes that underlie our perception of pictures have been studied extensively, only a few studies have investigated the relationship between early sensory processing and memory capacity for pictures (Bartlett, Gernsbacher, & Till, 1987; Cave, Bost, & Cobb, 1996; Engelkamp, 1990; Homa & Viera, 1988; Jolicoeur, 1987; Park & Mason, 1982). To help bridge this gap, we studied the effect of color, exposure duration, and contrast on the recognition memory for natural images.

Color and contrast are ideal candidates for such an investigation because their early sensory processing is quite well understood. Light of different wavelength is absorbed by three distinct classes of cones and subsequently processed in three color-opponent channels: red–green, blue–yellow, and black–white (for reviews, see Gegenfurtner & Sharpe, 1999; Kaplan, Lee, & Shapley, 1990; Lennie & D'Zmura, 1988; Nathans, Merbs, Sung, Weitz, & Wang, 1992; Stockman, MacLeod, & Johnson, 1993; Stockman & Sharpe, 1998). Less is known about the cortical processing of color, however. One popular hypothesis (Livingstone & Hubel, 1987) postulates that color is processed independently of other sensory attributes (such as form, depth, motion) and that the role of color in early image processing is rather limited. Other investigators have suggested that color plays a highly specialized role in some image segmentation tasks, such as detecting ripe fruit amongst variegated foliage (Mollon & Jordan, 1988; Polyak, 1957; Walls, 1942). Finally, at an introspective level, color coding appears as if it might be important for the rapid identification and recognition of objects. Given such disparate views, we decided to measure the contribution of color to recognition memory and to investigate whether the contribution is at an early sensory level only, or whether it also extends to the representation of images in memory.

Color in Object Identification and Classification

Several studies have investigated the role of color information for object identification and classification. Generally, color is found to have little influence on object identification and classification, except for (slightly) faster object naming (Biederman & Ju, 1988; Cave et al., 1996; Davidoff & Ostergaard, 1988; Joseph & Proffitt, 1996; Ostergaard & Davidoff, 1985; Seamon et al., 1997). Ostergaard and Davidoff (1985) found a significant effect of color on object naming latencies using color versus black-and-white photographs of objects—provided that objects were presented in their natural color—but the magnitude of the effect, although statistically significant, was small. In an influential article, Biederman and Ju (1988) failed to find any such beneficial effect when measuring naming and verification latencies during object recognition comparing color photographs with line drawings. Wurm, Legge, Isenberg, and Luebker (1993) found that the addition of chromatic information both decreased the reaction time during object recognition and increased the recognition accuracy when comparing luminance-matched gray-scale and color photographs, but, again, effect size was comparatively small.

In Wurm et al.'s (1993) study, the advantage for colored images in their experiment was independent of the diagnosticity of the color of an object, that is, whether the color is intricately linked to the identity of an object (e.g., ripe bananas tend to be yellow). This finding, they argued, points toward a sensory (early) rather than a cognitive (late) locus of the superior recognition performance. Humphrey, Goodale, Jakobson, and Servos (1994) conducted a series of experiments using normal observers as well as a patient with visual form agnosia. They, too, found that chromatic information facilitated object naming. But, unlike in Wurm et al.'s study, the naming advantage was linked to color diagnosticity in Humphrey et al.'s (1994) study:

> We found, however, that the presence of colour speeded naming of the naturally coloured objects but not the artificially coloured objects relative to conditions without colour. This result suggests that the influence of colour is occurring at a higher level of visual analysis where the knowledge of object properties is represented. (p. 1473)

Similar conclusions were reached by Joseph and Proffitt (1996) who found that the stored color knowledge about an object was more influential in object recognition than the surface property color of the particular exemplar their subjects were presented with. Similarly, Mapelli and Behrmann (1997) concluded that perceptual or surface color only aids object recognition if shape cues are ambiguous and that the color advantage is one of top-down (cognitive) color knowledge, not sensory surface information, under such circumstances.

The current view on color in object identification is aptly summarized by Hanna and Remington (1996): "In general, color confers an advantage either when it is strongly associated with an object's identity or when sufficient processing time is allowed that the object enjoys conceptual, not perceptual, processing" (p. 323).

The independence of color information and object identification is consistent with edge-based accounts of object recognition (Biederman, 1987; Lowe, 1985; Marr, 1982). Biederman's (1987) volumetric primitives (geons) or Lowe's (1985) wire-frame-based image representation codes are direct descendants of Marr's (1982) computer-vision inspired notion of early vision's task being to provide a symbolic, discrete representation of the visual world in terms of achromatic edges, lines, and junctions. Such edge-based accounts assume that segmentation is done on the luminance image and that color and other surface properties like shading and texture are "filled in" after the initial parsing operation has been completed, aiding object recognition only under conditions of image degradation or ambiguity, and if sufficient processing time is allowed.

Further evidence for edge-based accounts of object recognition stems from priming studies finding that priming is insensitive to surface features, particularly color (Cave et al., 1996; Seamon et al., 1997). Finally, Stefurak and Boynton (1986), Zimmer (1993), and Hanna and Remington (1996) all found that color and form appear to be coded independently by showing that subjects were generally very bad at remembering the color in which objects were initially presented, even if they recognized them as having been presented before.

Color in Recognition Memory

A second line of inquiry into the role of color in visual cognition has been directed toward recognition memory of images and natural scenes as opposed to identification, naming, or classification of isolated objects. It has become clear that there is enormous memory capacity for storing pictures of objects and scenes (Nickerson, 1965; Shepard, 1967; Standing, 1973). Borges, Stepnowsky, and Holt (1977) found that, for adults, recognition memory was better for colored pictures and words of objects than for black-and-white versions. However, the pictures in the study were not matched in their luminance. Further, instead of having to perform a straightforward recognition test, subjects were presented with the name of an object and asked whether they previously had seen such an object and, if yes, in which mode (color photograph, black-and-white photograph, or word). However, Anglin and Levie (1985) failed to find any recognition memory advantage for color photographs over black-and-white photographs. Again, however, the luminance distributions of the colored and black-and-white pictures were not matched. Furthermore, they intermixed the photographs with words of objects and line drawings, possibly encouraging the subjects to use verbal encoding schemes, which would tend to abstract away from surface features like color. Thus, features of the experimental design of both the Borges et al. and Anglin and Levie studies make it difficult to draw clear-cut conclusions about the importance of color for image recognition.

Homa and Viera (1988) found a clear advantage in retention of color photographs over black-and-white photographs and elaborated and nonelaborated line drawings of semantically related images. Homa and Viera's main independent variable was retention interval (ranging from immediate recall to a 12-week delay). They concluded that at least some surface information must be stored in memory to account for the superior recognition performance of color photographs over black-and-white ones. Suzuki and Takahashi (1997), too, found a significant recognition memory advantage for color pictures of urban scenes over black-and-white photographs, both during immediate recall and, even more pronounced, after a 1-week retention interval.

The problem of the nonmatched luminance distributions of the color and black-and-white images none withstanding, the experimental support for a role for color in recognition memory is in line

with surface-based models of early visual processing (e.g., Farah, 1990; Farah, Rochlin, & Klein, 1994). Surface-based theories argue that surface properties such as color and texture together with contour information are processed in parallel and all contribute, at an early processing stage, to the internal visual representation of the world.

Multiple Memory Systems

Object identification and classification fail to show a significant involvement of color information, supporting edge-based accounts of object recognition. Conversely, color recognition experiments of natural scenes appear to show a color recognition memory advantage, in line with surface-based theories. Schacter and Cooper's (Cooper & Schacter, 1992; Cooper, Schacter, Ballesteros, & Moore, 1992; Schacter, Cooper, & Delaney, 1990; Schacter, Cooper, Delaney, Peterson, & Tharan, 1991) distinction between a *structural description system* and an *episodic memory system* as two—not necessarily exhaustive—components of a multiple memory system might offer a reconciliation of the literature. Object recognition and identification of isolated objects might predominantly tap into a (perhaps view-independent) edge-based, structural object recognition memory system. Recognition memory for natural scenes providing rich surface information might, however, tap into a more surface-based episodic memory system, in which the surface attribute color might well be part of the memory representation. We term this advantage for color in (episodic) recognition memory for natural scenes as *cognitive facilitation*, because its locus is subsequent to sensory processing: it arises from the representation of color within memory.

One important caveat is that performance in a recognition memory experiment—in the absence of a formal theory of similarity—boils down to the experimenter's choice of distractors during recall (see Carmichael, Hogan, and Walter, 1932; Daniel, 1972; Snodgrass & McCullough, 1986; Standing, 1973). For the experiments reported in this article, pilot studies ensured that, overall, recognition memory performance was approximately 80% correct under the most favorable conditions (to avoid floor and ceiling effects). This indirectly verified our picture selection procedure (described below) in that it ensured an adequate level of "psychological similarity" between all images used, a crucial prerequisite for a recognition memory study.

Color in Image Segmentation

One striking difference between the object recognition and identification studies on the one hand, and the natural scene recognition memory experiments on the other, is that, for the object studies, the to-be-recognized categorized or remembered objects were presented in isolation against a uniform background. A possible evolutionary advantage for color over luminance-based vision may lie, however, in superior segmentation of objects from textured backgrounds (Davidoff, 1991; Polyak, 1957; Walls, 1942). The hypothesized role of color in image segmentation is not inconsistent with results from the visual search literature in which color is reported to be one of those stimulus characteristics that lead to fast segmentation ("pop out"), or a "parallel search" (e.g., Treisman & Gelade, 1980; Treisman & Gormican, 1988; Wolfe, Cave, & Franzel, 1989; but also see Geisler & Chou, 1995).[1]

Furthermore, recent computer-vision algorithms that combine chromatic and luminance information to derive a meaningfully segmented representation of visual scenes appear to be more successful than those that only use luminance information (Healey, 1989, 1992; Lee, 1990; Perez & Koch, 1994).[2]

Thus, it is conceivable that color helps the visual system to parse (complex) images both faster and more efficiently, achieving superior segmentation into separate, identifiable objects, and thereby aiding the semantic "tagging" of visual objects. This is likely to result in better recognition for colored images because of their "richer" representation in memory. Such a segmentation-based facilitation of recognition memory found with natural scenes would, hence, not be due to color being part of the memory representation even within the episodic memory system (which we call a cognitive facilitation). We will refer to this possible advantage of color in recognition memory henceforth as a *sensory facilitation,* because it is assumed to happen at an early level of visual processing—physiologically, psychologically, and in terms of processing time.

Hence, a demonstration of superior memory for colored natural scenes in itself does not prove that color is part of the memory representation. In line with this reasoning, Suzuki and Takahashi (1997) reported that recall for the color mode of pictures is worse than recognition itself, suggesting that memory for color per se is not the only source of the color recognition superiority, but that other factors, perhaps improved image segmentation or increased distinctiveness of features highlighted by color, contribute to the enhanced recognition memory (Hanna & Remington, 1996; Stefurak & Boynton, 1986; Zimmer, 1993).

Finally, if color's sensory contribution to recognition memory is due to improved image segmentation, then it may not be surprising that Humphrey et al. (1994) and Joseph and Proffitt (1996) failed to find much sensory facilitation owing to color: their stimuli were, in fact, already segmented away from the background. To avoid such complications in our experiments, we chose images of natural scenes as stimuli. In these scenes, one or more objects were embedded in their natural backgrounds.

Experimental Rationale

Although the multiple memory system hypothesis could in principle reconcile a large part of the literature on the influence of color information on visual cognition, several important issues need to be addressed.

First, the superiority of color recognition memory for natural scenes needs to be demonstrated using carefully luminance-matched color and black-and-white images (Experiment 1). Second, because of the difficulty in defining contrast for chromatic

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[1] It should be noted that it is difficult to compare different visual cues without converting them into the same "currency" within which comparisons will then be meaningful. Such conversions, however, are far from straightforward.

[2] Clearly, the success of the latest machine-vision algorithms cannot be taken as direct evidence for any color involvement in human image segmentation, but the results might at least be considered. Indeed, many of the currently espoused cognitive models of visual processing are firmly rooted in (older) machine vision, a point previously made by Humphrey et al. (1994, p. 1458) and Brodie, Wallace, and Sharrat (1991).

stimuli, the effect of image contrast on recognition memory has to be explored to exclude the possibility that superior recognition memory for colored images actually stems from contrast artifacts (Experiment 2). Third, to demonstrate that the surface feature color contributes to the superior recognition memory performance because it is part of the (episodic) memory representation (cognitive facilitation), presentation and query color have to be varied independently. If improved color recognition memory is solely a result of the superior image segmentation process (sensory facilitation)—highlighting important features, or allowing the extraction of more objects to be streamed into the object recognition system (cf. Suzuki & Takahashi, 1997)—then the query color should not matter, and superior recognition memory should result from the presentation of color images during the study phase, independent of query color, given sufficient processing time during the query phase (Experiment 3). Fourth, color is well known to be a highly "salient" visual surface feature (Davidoff, 1991). Experiments need to be conducted to disentangle color memory effects from attentional or salience effects (Experiment 4). Finally, we explore the issue of color diagnosticity and again of attentional effects in an experiment comparing natural scenes colored using false or their "true" colors (Experiment 5).

In all five of our experiments, the query phase commenced immediately after the study phase. According to the results obtained by Suzuki and Takahashi (1997), this is a conservative procedure to adopt: The relative improvement of color over black-and-white photographs increased with retention interval in their study.

From a less cognitive and more sensory viewpoint, we systematically vary several parameters that strongly affect the early sensory processes underlying our perception of pictures—color, presentation time, and stimulus contrast—in Experiments 1–3.

Considered together, the results should help clarify the relation between early sensory processing and memory capacity for pictures (see also Bartlett et al., 1987; Cave et al., 1996; Engelkamp, 1990; Homa & Viera, 1988; Jolicoeur, 1987; Park & Mason, 1982).

Experiment 1: Exposure Duration

Method

Procedure. The experiment consisted of two phases: A presentation phase, in which subjects were sequentially shown a set of 48 images of the kind shown in Figure 1, and a query phase, in which subjects' recognition memory for the images was tested. For each subject, each of the 48 images were first presented at a duration of either 50, 200, 400, 533, 800, or 1,067 ms, with a 7-s interval between successive images. We ensured that all subjects saw 12 images per category, 6 in color and 6 in black and white—one image per category, color presentation mode, and presentation time. In the immediately following query phase, the same 48 images were randomly intermixed with 48 new images, and the subject's task was to indicate whether he or she had already seen each image during the presentation phase. The query phase was self-paced and each image was presented until the subject gave a response (yes–no answer).

Stimuli. The images were chosen from four different categories: green landscapes with fields and trees (Figure 1, upper left), flowers (Figure 1, upper right), rock formations (Figure 1, lower left), and man-made objects (Figure 1, lower right).

Images were not formally screened for category membership, but when asked, subjects were able to assign the images to the different categories without any difficulty. No categorical screening procedure was used simply because there is no formal or computationally successful theory of similarity or category membership that would allow an objective similarity metric to guide the picture selection process (see, e.g., Barsalou, 1989; Herrnstein, 1985; Snodgrass & McCullough, 1986; but also see Edelman,

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 image is from Category 3, rock formations; and the bottom-right image is from Category 4, man-made objects. All the landscapes were quite similar in color and shape. Flowers differed widely in color, but 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.

1999). Pictures were selected by a procedure similar to that described by Potter (Potter, 1976; Potter & Levy, 1969). As mentioned previously, pilot studies ensured that, overall, the chosen images were correctly remembered approximately 80% of the time at the longest viewing duration. This we take as an indirect verification of our picture selection procedure in that it ensured an adequate level of "psychological similarity" between all the images within a category. Both targets and distractors were randomly and independently chosen for each subject from the set of psychologically similar pictures.

We hypothesized that the critical differences between our categories were that (a) images in Category 1 (landscapes) were all similar in both color (green) and in achromatic structure (i.e., those aspects, such as grass and leaves, the shape and texture of which are easily recognized, and thought to be extracted from the achromatic image); (b) images in Category 2 (flowers) differed greatly in color and very little in their achromatic structure; (c) images in Category 3 (rock formations) differed greatly in achromatic structure but very little in color, and (d) images in Category 4 (man-made objects) differed widely in both color and achromatic structure.

In total, our database of pictures consisted of 96 images, 24 within each of the four categories. In all our experiments and for each subject, 12 images per category were randomly chosen as targets, resulting in a presentation phase of 48 images per subject. The remaining 48 images, again 12 per category, were the set of distractors. Images were randomly assigned to conditions for each subject. Of the set of 48 target images, half were randomly chosen to be presented in color, the other half in black and white. The luminance component of the images was measured and identical under both conditions; the space-averaged mean luminance was approximately 35 cd/m^2. Each image was immediately followed by a mask consisting of pixel blocks randomly chosen from color space for color pictures, and from black-and-white space for black-and-white images. Images that were presented in color (or black and white) during the presentation phase were always presented in color (or black and white) during the query phase. Subjects were told that they were taking part in a recognition memory experiment before the beginning of the presentation phase; the presentation phase took approximately 5 min, and the query phase typically took 15 min to complete.

Experiments were run on a Silicon Graphics Indigo II (Silicon Graphics, Mountain View, CA) workstation with a 24-bit frame buffer. 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 1,067 ms. After the image presentation, a mask was presented for 200 ms, followed by a uniform gray field at the mean luminance.

Subjects. Thirty-six students at the University of Tübingen (20–25 years old) served as subjects in this experiment. All of them had normal or corrected-to-normal visual acuity and normal color vision. They were paid for their participation.

Results

Figure 2 shows the results of Experiment 1. The mean hit rate averaged across category, image, and subjects is plotted (*y*-axis) against exposure duration of the images during the presentation phase (*x*-axis). Each data point is based on 144 observations, 4 per subject. There was no difference in the false-alarm rate between luminance (0.169) and color (0.156) distractors, as indicated by the dashed lines at the bottom of the graph (long and short dashes, respectively).[3] Given that no exposure durations could be assigned to the distractors—as they were included in the presentation phase—only hit rates are depicted. An analysis of variance (ANOVA) revealed significant main effects for exposure duration, $F(5, 175) = 56.83$, $p < .01$; image category, $F(3, 105) = 17.03$, $p < .01$; and presentation mode (color vs. black and white), $F(1, 35) = 2.84$, $p < .01$. A weak interaction occurred between expo-
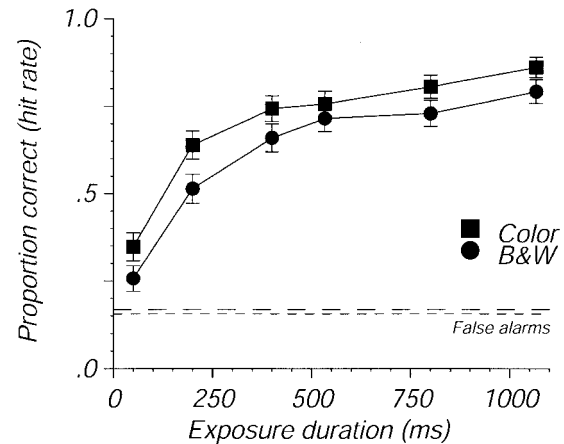

Figure 2. Proportion of correctly recognized images (hit rate) as a function of exposure duration of the images during the presentation phase. B&W = black and white.

sure duration and image category, $F(15, 525) = 1.82$, $p < .05$. Here, and in all the following data figures, the error bars plotted correspond to plus or minus one standard error.

The effect of exposure duration is typical for transfer to short-term memory (Gegenfurtner & Sperling, 1993; Loftus, Duncan, & Gehrig, 1992). Performance increases rapidly at first, then approaches an asymptotic level near 500 ms. Further, there are significant differences between image categories. Subjects found the man-made objects easier to recognize (mean correct = 86.4%) than the rock formations (mean correct = 73.5%), flowers (mean correct = 68.1%), or green landscapes (mean correct = 67.8%)—hence, our image selection through our pilot study did not work perfectly in that recognition performance depended significantly on image category. However, given that the mean correct performance was above 65% and below 90% correct for all categories, and therefore neither close to floor nor to ceiling performance, these differences between categories should not influence any of our conclusions. The interaction between exposure duration and image category was mostly owing to the better performance for man-made objects (Category 4) than for the other categories at the very short presentation durations.

The important finding within the context of this article is the effect of color versus black-and-white presentation. In Figure 2, the squares forming the top curve show performance for the colored images, the circles forming the bottom curve show performance for black-and-white images. There is a difference of about 8% between the two conditions, and it is independent of exposure duration; that is, the performance improvement for colored images is the same at all exposure durations tested (between 50 ms and 1 s). The effect size is 0.66 standard deviations.

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[3] We present our results in terms of the hit rate because of the constant false-alarm rate—given a constant false-alarm rate, other common measures like d', or measures correcting for false-alarm rates, yield essentially identical results.

Discussion

These results indicate a strong effect of color on recognition memory. Although a performance improvement of 8% might initially appear rather small, it has to be evaluated within the context of our image selection: Our images were chosen to be difficult to discriminate to avoid ceiling effects. We believe that there is no other image manipulation that could increase the level of asymptotic performance in such a significant fashion.

Figure 3 shows the performance for each category for color (left bar) and black and white (right bar), averaged across all presentation durations. As previously mentioned, performance differed significantly between the different categories. The green landscapes (Category 1) were most difficult to remember, flowers (Category 2) and rock formations (Category 3) were intermediate, and the man-made objects (Category 4) were easiest. However, hit rates are higher for color images in all categories. False-alarm rates were approximately the same for colored and black-and-white images; the level was roughly constant for images of Categories 1, 2, and 3 (green landscapes, flowers, and rock formations, respectively) but was notably lower for images of Category 4 (man-made objects). No interaction was found between image category and presentation condition, $F(3, 105) = 0.66$, $p > .10$.

Our expectation when we ran these experiments—and selected the images—was that the influence of color on recognition memory would differ for the different image categories. In Categories 2 (flowers) and 4 (man-made objects), there was a large variation in color between the different images; whereas in Category 1 (green landscapes), the images appeared all predominantly green, and in Category 3 (rock formations), the images were all predominantly reddish brown. However, the ANOVA revealed no interactions between image category and presentation mode nor between presentation mode and exposure duration. To explore this issue in more detail, we looked at performance as a function of the individual images to determine for which images color information is important; that is, for which images there is a reliable and large difference in performance between color and black-and-white presentation mode.

Figure 4 plots hit rate for black-and-white presentations on the y-axis against hit rates for color on the x-axis for each image averaged across all subjects. The high correlation of 0.63 across all
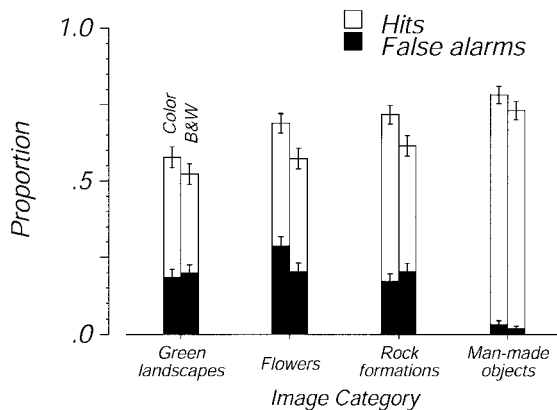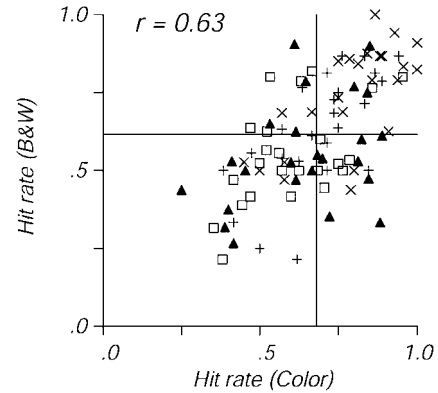

Figure 4. Recognition performance for the 96 images used in Experiment 1. The x-axis plots the hit rate for a particular image when it was presented in color. The y-axis plots the hit rate of the same image when it was presented in black and white. The heavy horizontal and vertical lines indicate the average performance under these two conditions. Different symbols indicate the four different image categories: green landscapes (open squares), flowers (filled triangles), rock formations (+s), and man-made objects (×s). The coefficients of correlation between color and black-and-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. B&W = black and white.

four categories suggests that about 40% of the whole variance in recognition performance may be attributed to the luminance components of the images, that is, the "implicit" black-and-white image within the color images. There are, however, differences between categories: The correlations by categories are 0.59 for the green landscapes (Category 1), 0.67 for the rock formations (Category 3), 0.68 for the man-made objects (Category 4), but only 0.39 for the flowers (Category 2). Thus, everything else being equal, color seems to play a larger role for the flower images than for the other images, but only in determining which of the individual flower images can be better remembered out of the entire set.

We also analyzed individual images with respect to their mean (average) color and variance of colors, but no systematic relationship was found between these properties and recognition performance for the images. The question of which particular aspect of color in images supports easy recognition will have to be answered with stimuli that can be controlled and manipulated more easily (see Sachtler & Zaidi, 1992).

Experiment 2: Contrast

One potential and serious problem with comparing colored and black-and-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 achromatic or black-and-white luminance variations, the contrasts for all three types of photoreceptors are equal at each pixel—that is, why they appear achromatic to us. Contrast of the whole image can then be defined as the maximum of all pixel contrasts. For color images, the situation is more difficult, because

Figure 3. Proportion of hits and false alarms for each image category. B&W = black and white.

at each pixel the contrasts of the three photoreceptors will typically be different. One could use a 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 and white could simply be owing to an increased image contrast in the color images. To control for this parameter, we varied image contrast in Experiment 2.

Method

All methods were identical to those used in Experiment 1, except that the exposure duration was constant at 1 s, and six different image contrasts were used: 5%, 10%, 20%, 40%, 70%, and 100%. These contrasts were specified as the percentage of contrast 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-and-white and color images, so that at each contrast level the luminance components of the colored and black-and-white images were identical. Thirty-four different subjects participated in Experiment 2.

Results

The results are shown in Figure 5. Hit rate on the *y*-axis is plotted against contrast on the *x*-axis. Again, there is an advantage for color over the black-and-white images, except for the very lowest contrasts of 5% and 10%, where the images were hardly visible, and, consequently, performance was essentially at chance level. What is important to note is that at contrast levels above 40%, recognition memory performance is independent of contrast—for images presented at 40%, images had less than half the contrast they have under natural viewing conditions, and, subjectively, appeared very faint, without any decrease in memory performance. Thus, contrast effects are very unlikely to account for the difference in recognition memory performance between color and black-and-white images in Experiment 1. This also excludes the possibility that the minimal contrast variations, which unavoidably arise from chromatic aberration within natural images
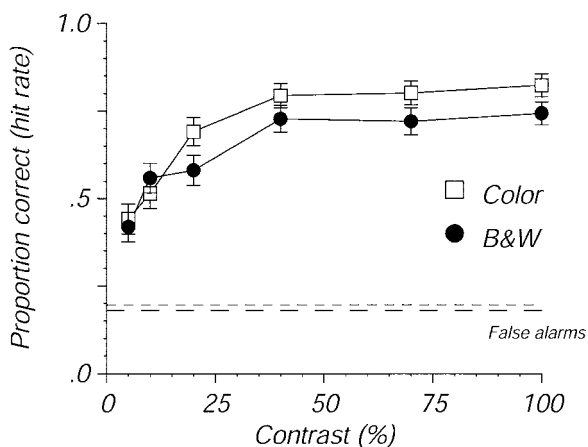
(Marimont & Wandell, 1994), account for the difference in recognition performance between color and black-and-white images.

Experiment 3: Coding Versus Retrieval

In Experiment 2, contrast was ruled out as a possible candidate to explain the superior recognition for color images. In Experiment 3, we attempt to disentangle improved image segmentation (sensory facilitation) and internal color representation (cognitive facilitation) as possible sources of the superior recognition performance. In particular, we used a procedure to determine if sensory facilitation by itself could explain the performance differences between colored and black-and-white images.

Method

The methods were the same as those used in Experiment 2, save that all images could be tested either in color or in black and white, regardless of how they were originally presented. Exposure duration was held constant at 1,000 ms. Only three different levels of contrast were used: 10%, 50%, and 100%. Thirty-one new subjects participated in Experiment 3. We counterbalanced the assignment of images to subjects in this and all subsequent experiments. If an image was presented in color for one subject, it was presented under the same conditions, but in black and white for another subject. The same counterbalancing was used for the query phase.

Results

An ANOVA revealed main effects of image category, contrast, and presentation mode. In addition, there was a significant interaction between presentation mode and query mode, $F(1, 30) = 8.209$, $p < .01$. Figure 6 shows the interaction effect averaged across contrasts and subjects. Performance for images presented in color was significantly worse when the images were queried in black and white, and vice versa performance for images presented in black and white was worse when the same images were queried in color. However, as in the above experiments, there was a significant advantage for color presentation, at least when queried in color, $F(1, 30) = 4.576$, $p < .05$.

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 data sets should superimpose.[4] This is clearly not the case, and we conclude that sensory facilitation alone cannot account for the performance difference. The issue of whether cognitive facilitation by itself suffices to explain our results is addressed in the General Discussion, when considering the results of all five experiments together.

Experiment 4: Effects of Salience

Color is a very salient visual attribute, and it is an effective means of engaging visual attention (e.g., Davidoff, 1991). Hence, to establish that color indeed enhances (episodic) recognition

Figure 5. 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. B&W = black and white.

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[4] One should remember that the query phase was self-paced. Fast segmentation processes are, hence, very unlikely to play a role during the query.
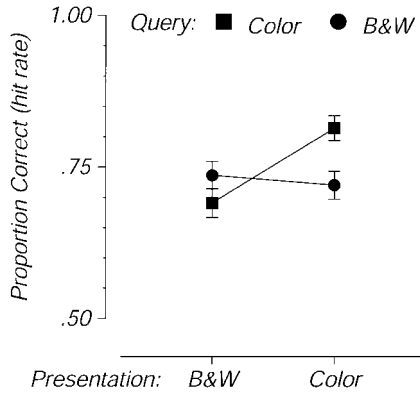
Figure 6. Results of Experiment 3. The *x*-axis plots whether images were presented in black and white or color. The *y*-axis plots the proportion of correctly recognized images for images queried in color and black and white. B&W = black and white.

memory and improves image segmentation, it is paramount to exclude the possibility that the superior recognition memory performance we found in our Experiments 1, 2, and 3 resulted from the unspecific effect that subjects "attended more to" or were somehow "alerted by" the colored images.

Method

The methods were similar to those used in Experiment 1, with some exceptions. First, exposure duration was held constant at 1000 ms. Second, images were always presented and tested in black and white. Third, all stimuli were presented within a frame: In Experiment 4A, we attached a black frame to half of the images. Images presented with a black frame during learning were also tested with a black frame. In Experiment 4B, we used colored frames instead of the black frame. A colored frame—randomly chosen as being either red, green, or blue—was attached to half of the images.[5] Again, images that were presented with a colored frame during the presentation phase were also presented with a color frame during the subsequent testing phase. Twenty different subjects participated in Experiment 4A and another twenty participated in Experiment 4B.

Results

Table 1 shows the results of Experiment 4A; Table 2 shows the results of Experiment 4B. Inspection of Table 1 suggests that the presence or absence of a black frame has no influence on recognition memory: Proportion correct across all images equaled 77.7% and 77.4% for the no-frame and black-frame conditions, respectively. Similarly, hit and false-alarm rates do not differ substantially across experimental conditions, and none of the differences were significant.

Table 1
Effect of Black Frames on Recognition

Response measure	No frame	Black frame	$t(19)$	p
Proportion correct	.7773	.7742	0.27	.788
Hit rate	.6933	.7100	1.45	.163
False alarms	.1388	.1617	1.08	.275

Table 2
Effect of Colored Frames on Recognition

Response measure	No frame	Colored frame	$t(19)$	p
Proportion correct	.7698	.8000	2.51	.021*
Hit rate	.6771	.7312	2.48	.023*
False alarms	.1375	.1313	0.57	.445

* $p < .05$.

For the colored frames of Experiment 4B, however, there is a significant improvement in recognition memory, as shown in Table 2: Proportion correct improves from 77.0% to 80.0% if colored frames surround the images during presentation and query phase. This increase in proportion correct is statistically significant, $t(19) = 2.51$, $p < .05$; it results from an increased hit rate (67.7% vs. 73.1%), $t(19) = 2.48$, $p < .05$, with the false-alarm rate remaining unchanged (13.8% vs. 13.1%), $t(19) = 0.57$, $p > .40$. This pattern of results is consistent with the hypothesis that colored frames increase attention or vigilance during image encoding, resulting in better retention. It should be noted that the presentation of frames per se did not have any influence on recognition memory.

Discussion

Color is a highly salient visual attribute, and presenting images within an irrelevant color frame improves recognition memory, presumably by increasing subjects' attention. However, the *effect size* of the improvement, although statistically significant, is considerably smaller than those reported in Experiments 1, 2, and 3 between color and black-and-white images of natural scenes. The improvement is only 3%, whereas it was found to be 8% in our earlier experiments. Of importance, these differences occur at the same absolute level of performance. Figure 2 shows the results of Experiment 1: Absolute levels of performance were approximately 78% correct for black and white and 86% correct for color at the longest presentation time of 1,000 ms. Here we find a performance of 77.4% across Experiments 4A and 4B for the black-and-white images—the same as the black-and-white performance of Experiment 1—but only 80% for the black-and-white images with color frames. Attentional or saliency effects clearly form part of the color advantage, but by themselves they cannot explain the effect size observed in Experiments 1, 2, and 3.

Experiment 5: Natural Versus False Colors

One surprising aspect of our data reported in Experiment 1 is that we failed to find evidence that either color gamut or color diagnosticity improves retention: Image retention for all four categories—green landscapes, flowers, rock formations, and manmade objects—benefited similarly from the color addition despite the large variation in color gamut and color diagnosticity across the four image categories. In Experiment 5, we investigated whether memory retention is sensitive to natural versus false

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[5] We introduced the black frame to be able to distinguish saliency effects due to the frame alone from those due to color.

colors, because all stimuli used thus far were carefully calibrated photographs of natural scenes. Even if their gamut was small (e.g., green landscapes or rock formations), or diagnosticity was low (man-made objects), none contained obviously false colors such as green skies or bluish skin tones. If, as Experiment 3 might be taken to suggest, the surface property color is retained in some form of episodic memory, it is interesting to investigate whether color per se improves memory, or whether unnaturally colored scenes are not remembered better than black-and-white scenes because the episodic memory system contains a form of "reality filter."

Additionally, an experiment with false colors offers another paradigm within which to assess the influence of color on attention. Experiment 4 suggests that color, per se, increases attention and thereby improves recognition memory. On the basis of the effect size of the improvement, we argued that this attentional effect by itself is very unlikely to account for the large improvement seen in Experiments 1, 2, and 3. One might argue, however, that although color borders increase attention, they do so less than fully colored images. Thus, the argument would be that the difference in effect size merely reflects the difference in saliency. Results obtained with natural and false colored images, however, are not subject to such a criticism, as both types of images should be equally salient.

Method

The methods were similar to those used in Experiment 1, except that, first, exposure duration was held constant at 1,000 ms, and, second, images were presented and tested either in black and white, full color, or false color. The black-and-white and full color modes were identical to the ones in Experiment 1. The false colors were generated by pixelwise exchanging the red and green, and the blue and yellow components of the images. The luminance of each pixel was not changed. These color-opponent pairs—red and green, and blue and yellow—were defined with respect to the well-known second stage, color-opponent mechanisms of human and primate vision defined both by psychophysics (Krauskopf, Williams, & Heeley, 1982) and physiology (Derrington, Krauskopf, & Lennie, 1984). For each pixel, the RGB values were first transformed into the color-opponent space, and then the signs of the red–green and blue–yellow coordinates were inverted, and finally values were transformed back into the RGB space of the display monitor. A potential consequence of the transformation procedure is that the inverted values may no longer fit into the gamut
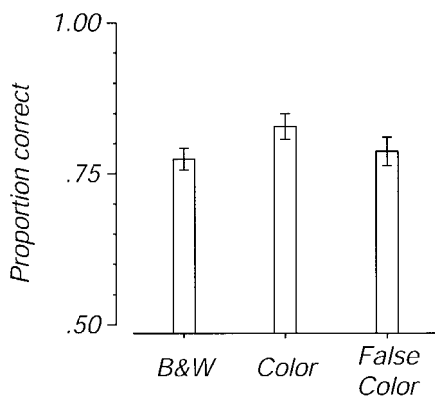

Figure 7. Results of Experiment 5. Images were presented in black and white, in color, or in false color. The *y*-axis plots proportion of correct responses. B&W = black and white.

Table 3
Effect of False Colors on Recognition (Performance)

Response measure	Black & white	Color	False color
Proportion correct	.7743	.8281	.7865
Hit rate	.6910	.7674	.7153
False alarms	.1424	.1111	.1424

of the monitor. Fortunately, this typically happened for less than 5% of the pixels. For those pixels that were outside the gamut of the monitor, the corresponding color values were fit into the gamut by reducing the saturation slightly. The overall effect of the false color manipulation was to produce highly unnatural looking pictures, with, for example, bluish skin tones or reddish grass tones. It is important to note that this method of creating false colors leaves the image structure unchanged: color-object boundaries are still color-object boundaries, and the luminance image does not change either. Twenty subjects who had not participated in any of the other experiments participated in Experiment 5.

Results

Figure 7 shows proportion correct recognition as a bar chart, with the three conditions (black and white, color, and false color) along the *x*-axis.

Table 3 shows proportion correct, hit rates, and false alarms for the three conditions; Table 4 shows the results of pairwise *t* tests on the proportions correct. As in all previous experiments, color images are better remembered than black-and-white images (82.8% correct vs. 77.4%; $p < .05$). False colored images, however, are not remembered better than black-and-white images (78.7% correct vs. 77.4%; $p < .58$). The difference between naturally colored and false colored images (82.8% correct vs. 78.7%) approaches significance ($p < .07$). Again, as before, the improved memory performance for naturally colored images over black-and-white and falsely colored images is largely due to an increased hit rate and not to differences in the false-alarm rate.

In addition, we calculated the correlation coefficient between correctly remembered images between the three different conditions across subjects. The correlation coefficient, ρ, equals 0.8545 between black-and-white and naturally colored images. This indicates that 73% of the total variance across subjects is accounted for by the subjects' memory: Subjects' color recognition performance was well predicted by their black-and-white recognition score. For the natural color and false color images, however, ρ is only 0.5566, significantly lower than 0.8545 ($p < .05$), and $\rho = 0.4768$ between false color and black-and-white images (significantly different, $p < .05$). Thus it appears as if factors other than subjects' (episodic) recognition memory played a major role in the recognition of the falsely colored images. Perhaps subjects focused predominantly on

Table 4
Effect of False Colors on Recognition (t Tests)

Comparison	$t(17)$	p
Black & white versus color	−4.7868	.019*
Black & white versus false color	−0.5552	.580
Color versus false color	1.9438	.069

* $p < .05$.

particularly unusually colored objects or scene regions instead of encoding the whole scene.

Discussion

Experiment 5 suggests an interaction between the surface colors of natural scenes and internalized knowledge about what colors occur in the world. False color images provide as informationally rich images as do natural color images, but the human visual and/or memory systems fail to exploit this additional information over black-and-white images. It should be noted that internalized knowledge about the gamut of natural colors differs from color diagnosticity: false colored man-made objects embedded in (false colored) natural scenes are remembered significantly worse than their "true" colored counterparts, despite the objects themselves having no true colors. However, not having a true color is not the same as having possibly any random color: even man-made objects, such as a car, have, for example, usually a fairly saturated color rather than any imaginable color.

Finally, the results of Experiment 5 provide further evidence that there is more to color in recognition memory than merely increased salience or attention: False colors are visually very salient, and there is no reason to suppose that they should be less salient than natural colors, but they do not result in improved recognition memory.

General Discussion

Our series of experiments strongly suggests that color plays an important role in recognition memory for natural scenes. Recognition memory for color images benefits from several factors.

1. Color Information Is Stored in Memory: Cognitive Facilitation

Particularly, the strong interaction observed in Experiment 3 between study and query color is incompatible with the notion that all color improvement is due to sensory facilitation. Further, the results of Experiments 4 and 5 demonstrate that attentional or saliency factors by themselves, or in combination with sensory facilitation, too, are insufficient to explain the large increase in recognition performance observed with color images. Hence, we are confident having demonstrated that the surface property color is, at least for (complex) natural images, stored in memory. Of interest, we find an interaction between conceptual prior knowledge about scenes and the benefit color bestows on memory retention. The results of Experiment 5 using false colors provide ample evidence that presentation of color per se (together with sensory facilitation and attentional alerting) is insufficient to boost recognition memory substantially: Sensory information (surface color) and conceptual knowledge must not be in conflict for the benefit to occur, that is, for the surface color to be actually stored in memory.

Finally, these results accord with previous, albeit less controlled, studies by Homa and Viera (1988) and Suzuki and Takahashi (1997). Taken together with the large literature failing to find (significant) effects of color on object recognition and identification (e.g., Biederman & Ju, 1988; Davidoff & Ostergaard, 1988; Joseph & Proffitt, 1996; Ostergaard & Davidoff, 1985), our results

support Schacter and Cooper's (Cooper & Schacter, 1992; Cooper et al., 1992; Schacter et al., 1990, 1991) notion of human multiple-memory systems.

At least two memory components are implied by our results and those of others on the effects of color on human memory: first, an achromatic object system (structural description system) and, second, a more surface-based episodic memory system storing color information, at least if this information accords with conceptual color knowledge. Clearly, this need not be an exhaustive list of possible components of such a multiple memory system.

This conclusion of ours is consistent with a recent study of Oliva and Schyns (2000) who found (diagnostic) color information to be beneficial in a scene recognition paradigm. Although our results agree with Tanaka, Weiskopf, and Williams (2001) on the importance of the surface property color as part of the memory representation of natural scenes, we differ in our conclusions: they argue for a single "shape+surface" model of object recognition, whereas we believe the literature is more readily accounted for in terms of the multiple memory systems hypothesis.

2. Color Increases Attention

Experiment 4 shows that the well-known saliency of color (Davidoff, 1991) can improve recognition memory, most probably owing to a nonspecific increase in attention. However, given that the effect size was much smaller than that observed in Experiments 1, 2, and 3, and given that false colors (Experiment 5) showed an even less-pronounced effect on recognition performance, we are led to conclude that saliency could at best provide a small fraction of the improvement we observed in recognition memory of color over black-and-white images.

3. Color Benefits From Improved Segmentation: Sensory Facilitation

Our conclusion that there is a sensory facilitation component associated with color information is more controversial than our other conclusions, and remains speculative. However, the relation between presentation duration and image recognition shown in Experiment 1 suggests that sensory factors, such as fast image segmentation, might also contribute. Hit rates for color and for black-and-white images as a function of presentation duration (Figure 2) were nearly perfect copies of each other, with color performance always being better by about 8%. The shape of the curves 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). Assuming that any benefits occurring at very short (50 ms) exposures would have to take place at a very early processing level, this result might be taken to support a low-level or sensory contribution to the color recognition memory superiority. (Particularly, because the effect is not only present but already fully developed at 50 ms.)

A second argument in favor of a sensory contribution to the observed color recognition memory superiority comes from the effect's independence of diagnosticity—exactly what would be predicted for sensory facilitation. 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. (The surface property "color" is much richer for flowers than, say, for rock formations). Nevertheless, all categories benefited similarly from the added chromatic information. A purely cognitive facilitation—through the enriched surface-property color of the images—would not necessarily be expected for the green landscapes and rock formations.

Finally, even if these arguments in favor of sensory facilitation should be rejected by future research, suggesting that the increased recognition performance was purely cognitive and attentional in origin, it should not be overlooked that the extraction of chromatic information must be very fast—the features coding color would have to be processed within the initial 50 ms. Given that within this time period absolute performance is still close to chance, this seems to imply that color is being processed faster than most other features, in conflict with physiological observations that processing of color is slower, if anything, in the visual cortex (Munk, Nowak, Girard, Chounlamountri, & Bullier, 1995). Unfortunately this intriguing issue is not easy to resolve within the present paradigm because presentation times shorter than 50 ms cannot be used. Memory performance for our stimuli would simply be too low. Using a delayed match-to-sample task paradigm, however, Gegenfurtner and Rieger (2000) recently found color recognition memory for images of natural scenes to be superior to that for black-and-white images of the same scenes for presentation times as short as 16 ms. The details of their results (see Gegenfurtner & Rieger, 2000, Figure 2, p. 807) provide strong evidence that some of the recognition memory advantage of color results from fast sensory processes, very likely from improved image segmentation.

4. Low-Level Sensory Parameters and Recognition Memory

As mentioned in our introduction, there have been comparatively few studies investigating the relationship between early sensory processing and memory capacity for pictures (Bartlett et al., 1987; Cave et al., 1996; Engelkamp, 1990; Homa & Viera, 1988; Jolicoeur, 1987; Park & Mason, 1982). Our results indicate that the sensory factors we studied—other than color—that is, presentation duration and contrast, play no major role once stimuli are visible. For presentation durations longer than 500 ms and for contrasts above 25%, memory performance reaches asymptotic values despite the complexity of our stimuli. Thus (low-level) sensory factors such as contrast appear to predominantly influence the transfer of information into short-term visual memory. Contrary to color, they do not appear to affect, or be part of, the representation of information in long-term memory.

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