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Object color affects identification and repetition priming

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We investigated the influence of color on the identification of both non-studied and studied objects. Participants studied black and white and color photos of common objects and memory was assessed with an identification test. Consistent with our meta-analysis of prior research, we found that objects were easier to identify from color than from black and white photos. We also found substantial priming in all conditions, and study-to-test changes in an object's color reduced the magnitude of priming. Color-specific priming effects were large for *color-complex* objects, but minimal for *color-simple* objects. The pattern and magnitude of priming effects was not influenced either by the extent to which an object always appears in the same color (i.e., whether a color is symptomatic of an object) or by the object's origin (natural versus fabricated). We discuss the implications of our findings for theoretical accounts of object perception and repetition priming.

Key words: Object identification and recognition, priming, implicit memory, color, meta-analysis, natural and fabricated objects, color symptomaticity.

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INTRODUCTION

Is it easier to identify an object when it is displayed in color rather than in black and white? Does the color of an object affect the magnitude of repetition priming effects? The present study examined these questions in order to advance understanding of the sensory, perceptual and cognitive processes that underlie the identification of common objects as well as the finding of repetition priming effects with such objects.

The identification of an object depends on many factors, especially its familiarity (Goodglass, Theurkauf & Wingfield, 1984; Wingfield, 1967) and the context in which it is displayed (Biederman, Mezzanotte & Rabinowitz, 1982). Nevertheless, for the vast majority of previous investigations of the basic sensory, perceptual and cognitive processes that mediate object identification and repetition priming effects, objects were displayed in isolation in order to examine the role of object internal attributes, such as edges and shapes as well as colors and other surface markings. Table 1 provides a comprehensive summary of the latter kind of investigations, more specifically, of those that examined the influence of colors and other surface markings (e.g., textures or fill patterns) – here called colors – by means of object identification and similar tasks.

The table entries highlight that in the majority of previous investigations, the same objects were presented for multiple trials. Thus, the findings from these studies do not permit us to separate the effects of colors on baseline identification performance (i.e., in a condition where an object is encountered for the first time) from those due to color-specific repetition priming (i.e., from the influence of one on the next presentation of the same object). More important for the objectives of the present study, this limitation does not apply to the few studies listed in the first section of Table 1 where each object was presented only once. This collection of studies used different types of stimulus materials (e.g., photographs, line-drawings) and different types of color-manipulations (e.g., photos in color or black and white, outline drawings with lines in color or black and white) and although they employed different dependent tasks (e.g., naming, category decision making), each of them showed a positive influence due to color on identification. A simple sign-test based meta-analysis of the results of the studies where objects were displayed only once shows a clear advantage due to color, $p = 0.016$. Moreover, for both single and multi-exposure studies, 26 outcomes showed an advantage due to color, one was neutral and three showed a disadvantage due to color, $p < 0.001$. The theoretical challenge is to explain this body of findings.

The relationship between color and object-identity seems arbitrary, at least for most fabricated objects (e.g., a pen, a car), and thus, the color of an object displayed out of context is not diagnostic (i.e., seeing a yellow patch is not sufficient for identifying an object), nor does it seem to function like a symptom, by restricting the range of possible perceptual interpretations. For this reason, previous attempts to explain color-effects on object identification have eschewed models that postulate influences on high-level, top-down processes in favor of models where colors affect low-level sensory and perceptual processes, for example, the detection of edges and primitive shapes (Biederman & Ju, 1988; Marr & Nishihara, 1978).

One advantage of postulating this route of influence is its fit with existing accounts of object identification such as Biederman's recognition-by-components model (1987).

Table 1. *Review of studies that investigated effects of color on object identification and priming*

Reference	Object type	Test task	Color manipulation	Observed Color advantage?	Found the effect significant?
Identification/Single exposure					
Naming					
Davidoff & Ostergaard (1988), Exp. 1	64 natural and fabricated	Naming	CP vs. BWP	+	+
Humphrey *et al.* (1994), Exp. 2	80 natural & fabricated	Naming	CP vs. BWP	+	+
Humphrey *et al.* (1994), Exp. 3	30 natural	Naming	CLD vs. BWLD	+	+
Cave & Squire (1992), Exp. 2	200 objects	Naming	PFLD vs. LD	+	–
Other tasks					
Davidoff & Ostergaard (1988), Exp. 1	64 natural and fabricated	Size judgments	CP vs. BWP	+	–
Davidoff & Ostergaard (1988), Exp. 1	64 natural and fabricated	Non-/living decisions	CP vs. BWP	+	–
Davidoff & Ostergaard (1988), Exp. 1	64 natural and fabricated	Non-/living decisions	CP vs. BWP	+	–
Identification/Multi-exposure					
Naming tasks					
Ostergard & Davidoff (1985), Exp. 1	24 natural	Naming	CP vs. BWP	+	+
Ostergard & Davidoff (1985), Exp. 2	3 natural	Naming	CP vs. BWP	+	–
Ostergard & Davidoff (1985), Exp. 3	4 natural	Naming	CP vs. BWP	+	+
Price & Humphreys (1989), Exp. 1	100 natural and fabricated	Naming	CP vs. BWP	+	–
			CLD vs. BWLD	+	+
Brodie *et al.* (1991), Exp. 3	12 objects	Naming	CP vs. BWP	+	–
Wurm *et al.* (1993), Exp. 1	21 natural	Naming	CP vs. BWP	+	+
Wurm *et al.* (1993), Exp. 2	21 natural	Naming	CP vs. BWP	+	+
Wurm *et al.* (1993), Exp. 3	21 natural	Naming	CP vs. BWP	+	+
Tanaka & Presnell (1999), Exp. 3	24 natural and fabricated	Naming	CLD vs. BWLD	+	+
Biederman & Ju (1988), Exp. 1	25 fabricated and 4 natural	Naming	CP vs. BWLD	–	–
Biederman & Ju (1988), Exp. 2	25 fabricated and 4 natural	Naming	CP vs. BWLD	+	–
Biederman & Ju (1988), Exp. 3	25 fabricated and 4 natural	Naming	CP vs. BWLD	+	+
Other tasks					
Price & Humphreys (1989), Exp. 1	100 natural and fabricated	Classification	CP vs. BWP	~	–
			CLD vs. BWLD	+	+
Price & Humphreys (1989), Exp. 2	45 natural	Classification	CP vs. BWP	+	+
			CLD vs. BWLD	+	+
Brodie *et al.* (1991), Exp. 4	12 objects	Verification	CP vs. BWP	–	–
Biederman & Ju (1988), Exp. 4	25 fabricated and 4 natural	Verification	CP vs. BWLD	–	–
Biederman & Ju (1988), Exp. 5	25 fabricated and 4 natural	Verification	CP vs. BWLD	+	–
Joseph (1997)	24 objects	Verification	CLD vs. BWLD	+	–
Tanaka & Presnell (1999), Exp. 4B	24 natural and fabricated	Verification	CLD vs. BWLD	+	+
Tanaka & Presnell (1999), Exp. 2	24 natural and fabricated	Verification	CLD vs. BWLD	+	+
Priming					
Naming tasks					
Cave & Squire (1992)	200 objects	Naming	PFLD	+	–
Cave *et al.* (1996), Exp. 3	176 objects	Naming	PFLD	+	–
Cave *et al.* (1996), Exp. 1	128 objects	Naming	CLD	–	–
Cave *et al.* (1996), Exp. 2	64 objects	Naming	CLD	–	–
Srinivas (1996), Exp. 1	80 objects	Fragment completion	LD	+	–
Other tasks					
Srinivas (1996), Exp. 2	6 objects	Object decision	OCLD	+	–
Seamon *et al.* (1997)	6 possible and 6 impossible	Color liking	CLD	+	–
Wippich & Mecklenbrauker (1998)	60 objects	Color preference	CLD	+	+

Notes: CP = color photos, BWP = black and white photos, CLD = color line-drawings, BWLD = black and white line drawings, PFLD = pattern filled line-drawings (i.e., no fill vs. pattern fill), OCLD = outline color line-drawings (i.e., black outline on white background vs. white outline on black background).
The table does not include studies that investigated color effects on priming but confounded study-test color manipulation with other variables (e.g., used different object sets).

According to this model, objects are represented in terms of geons, basic geometric building blocks, and special terms that define relations between and among them (e.g., geon A is above geon B, geon C is to the right of geon B). Biederman assumes that in order to name or identify an object, the perceptual system computes a structural description – it determines the object's geons and the relations among them – and in turn, this description provides access to its name, and to information about its use, function and meaning (Biederman, 1987; Biederman & Gerhardstein, 1993). More importantly, according to the model, neither geons nor the relations among them are associated with specific color information, and thus, any influence of colors on object identification must be mediated by lower level processes, such as edge and shape detectors (Biederman, 1987; Marr & Nishihara, 1978).

The geon model also offers a plausible account for repetition priming effects. According to the model, the perception of an object strengthens its structural description and by this process facilitates the subsequent perception of the same object (Biederman, 1987). The model assumes that structural descriptions represent only fundamental, constitutive properties of objects; they do not incorporate incidental attributes that are unique to a particular occurrence of an object or that might serve to differentiate between two exemplars of the same object. This assumption helps to explain the previous finding that repetition priming effects are not affected by a number of study-test object attribute manipulations, for example, by changes in the size, the spatial location or the left-right orientation of an object (Biederman & Cooper, 1991, 1992; Cave & Squire, 1992; Cooper, Schacter, Ballesteros & Moore, 1992; Cooper & Schacter, 1992). By the same assumption, and consistent with the view that the only route through which colors can influence object identification is via enhanced edge and shape detection (and similar low-level sensory-perceptual processes), it would follow that repetition priming effects with objects should not be color specific (i.e., show an influence due to the specific colors in which objects are displayed at study and test).

A number of previous studies that are listed in the last section of Table 1 have explored this expectation, but their results are mixed and difficult to interpret. One difficulty stems from the fact that although six out of eight studies showed some evidence of color-specific priming, the amount of priming was significant in only one. This balance of outcomes is particularly unsatisfying because it may reflect merely a lack of power, implying that significant color-specific priming effects would have been revealed in all cases had the studies been more powerful. Even a preliminary examination of this speculation is difficult, however, because not a sufficient number of the published studies provide the information required for computing power estimates. Some support for a low-power account of the existing findings comes from an examination of the materials and color manipulations used in previous investigations. All of them used outlines of objects drawn in different colors or filled with different line-patterns. We believe that using these types of objects or displaying them in this manner is too weak a manipulation, one that provides too little color information, and this weakness may be responsible for previous failures to find substantial color-specific priming effects.

The object line drawings used in previous investigations permit another intriguing hypothesis about the failure to find color-specific priming effects. It may be that an outline drawing of an object is always or typically perceived as representing an object class – as a type, rather than as representative of a particular individual object – as a token, and in turn, this manner of perceptual processing may minimize or prevent the occurrence of color-specific priming effects. By implication, it follows that color-specific priming effects might occur only with items that are perceived as distinct, particular individuals. We expected that photos of common objects would be perceived in this manner, as object tokens. Based on this line of reasoning, we used photos of common objects for the present study and, in contrast to the existing ambiguous results we expected to find clear color-specific priming effects on object identification test performance.

We undertook the present study for several reasons, but mainly because the presence versus absence of color-specific priming effects with objects has potentially profound theoretical implications. Previous repetition priming research with common words has shown consistent, substantial effects due to study-test manipulations that focused on internal attributes, for example, the stimulus display type font (Graf & Ryan, 1990; Jacoby & Hayman, 1987), the display orientation (Graf & Ryan, 1990; Masson, 1986), the presentation modality (Graf, Shimamura & Squire, 1985; Jacoby & Dallas, 1981; Roediger & Blaxton, 1987), or the presentation voice (Church & Schacter, 1994; Craik & Kirsner, 1974; Schacter & Church, 1992). A number of theoretical accounts have been advanced to explain the finding of such format specific priming effects with words (Bower, 1996; Graf & Ryan, 1990; Mandler, 1981; Masson & MacLeod, 1992; Roediger, Weldon & Challis, 1989; Schacter, 1994; Tulving & Schacter, 1990). For this reason, it would seem that if a powerful, compelling study with common objects failed to reveal a color-specific priming effect (as predicted by the geon model, for example), this outcome would underscore the difference between word priming effects and object priming effects. Moreover, this outcome would highlight the need for different theoretical accounts for word and object priming effects. Alternatively, if a powerful study with common object tokens were to reveal color-specific priming effects similar to the display-format specific effects that have been observed with common words, such an outcome would favor efforts to construct a single theoretical account that can accommodate both words and objects.

The primary goal of the present study was to investigate whether the presence or absence of color information influences the identification of common objects as well as the magnitude of priming effects observed on the subsequent identification of such objects. To examine the influence of color on priming, we employed the same basic method as in previous studies of object priming (e.g., Biederman & Cooper, 1991; Cave, Bost & Cobb, 1996; Uttl & Graf, 1996). During the study and test phase of the experiment, participants were shown a series of black and white as well as color photos of common objects on a computer monitor, and their task was to name each object as quickly and accurately as possible. Color-specific priming effects would be evidenced by the finding of greater priming effects for objects that were displayed in the same color-format at study and test than for objects displayed in different color-formats at study and test (e.g., color at study versus black and white at test).

During both the study and test phase of the experiment, one-third of the objects were displayed in their "normal" upright orientation, whereas the remaining objects were displayed in unusual orientations – rotated in the plane of the page by either 120° or 240°. We used the unusual display orientations in order to slow down object identification, thereby to magnify the unique contributions of various factors that are assumed to determine identification test performance (see Kolers, 1973, 1976). Previous research has shown larger priming effects under conditions where identification was slower or more difficult (see Uttl & Graf, 1996). The display-rotation manipulation also permitted us to re-examine the previous claim that repetition priming effects with objects are specific to the orientation in which they are displayed for study and test (Murray, Jolicoeur, McMullen & Ingleton, 1993; Uttl & Graf, 1996).

The present study also examined three secondary questions about the processes that mediate identification and repetition priming effects with common objects: First, are these processes different for different types of objects, specifically, for natural versus fabricated objects? Humphrey, Goodale, Jacobson and Servos (1994) suggested that many studies reporting a color facilitation effect on identification have focused on materials such as fruits and vegetables, whereas studies failing to find a color influence on performance (e.g., Biederman & Ju, 1988) have used primarily fabricated objects, many of them achromatic (e.g., a metallic gray fork). To explore the possibility that object color influences the identification of natural but not fabricated objects, Humphrey *et al.* (1994) compared identification speed for objects with natural colors (natural objects), objects with artificial colors (colored fabricated objects), and achromatic objects. Consistent with expectations, the results showed a color advantage for natural objects only, but this type of advantage was not observed in other studies (e.g., Price & Humphreys, 1989). Moreover, to our knowledge, no prior study has investigated the influence of object origin on repetition priming. To fill this evidence lacuna and to re-examine the inconsistent effects of object origin, we investigated the influence of object origin (natural versus fabricated) on both identification and priming using black and white as well as color photos of objects.

A second question addressed by our study is whether the processes that mediate identification and repetition priming effects are modulated by an object's color complexity, that is, by the extent to which its colors form an elaborate or intricate pattern? If so, this could explain why some of the prior studies have failed to find effects of color on identification and priming. Consistent with this possibility, a study by Biederman and Ju (1988) included many objects that were monochromatic or achromatic (e.g., an old-fashioned camera, and old-fashioned rotary phone) and presented them either as color slides or line drawings derived from the color slides. Accordingly, the failure to find color effects in this study may be due to a weak color manipulation, due to using mainly monochromatic and achromatic objects. To further explore this possibility, for the present study, we used objects that were either color simple or color complex.

The third and final objective of the present study was to determine whether the processes that mediate identification performance and repetition priming effects with objects are influenced by whether or not colors serve a symptomatic function? We assumed that colors are symptomatic of an object to the extent to which that object always or typically is encountered in the same distinctive color or colors. Several previous investigations have explored the possibility that color might affect identification for objects with symptomatic colors, but the findings have not been consistent (e.g., Biederman & Ju, 1988; Tanaka & Presnell, 1999), perhaps because most studies used only a small number of objects. Biederman and Ju (1988) used only 29 objects in their investigation and Tanaka and Presnell (1999) used only 24 objects. By contrast, we used a much larger set of objects for the present study and displayed them either as color photos or as black and white photos rather than as line drawings.

To investigate these questions about object identification and repetition priming, we employed a fade-in identification procedure similar to the widely used picture fragment completion test (e.g., Biederman & Cooper, 1991; Cooper, Biederman & Hummel, 1992; Srinivas, 1996; Goodglass *et al.*, 1984; Weldon, Roediger, Beitel & Johnson, 1995); we used the same method also for our previous investigations on the influence of various object attributes on identification, repetition priming and explicit memory (e.g., Uttl & Graf, 1996). The fade-in identification test has several critical advantages over the picture fragment completion test. First, the fade-in identification test is more sensitive because it steps through 240 levels of fragmentation rather than only the six or seven that are typically used in various picture fragment completion tests. Second, the fade-in identification test allows for greater precision and reliability in measurement than other object identification tests (Uttl & Graf, 1996). And third, performance on the fade-in identification tests is typically uncontaminated by explicit recollection strategies (Uttl & Graf, 1996; Uttl, Graf & Siegenthaler, 2005).

METHOD

Participants and design

One hundred and forty young adults, recruited from the general population, were required for the object identification testing part of the experiment and they received US$30 for their participation. The design had four within-subjects factors: photo type at study (black and white versus color), study history (studied, non-studied), study phase display orientation (upright, rotated by 120° or 240°), and test phase display orientation (rotated by 120°, rotated by 240°). There was also one between-subjects factor, test type (black and white versus color), and 70 participants were randomly assigned to each between-subjects condition.

Two additional groups, each with 15 different young adults drawn from the same general population (i.e., a total of 30 additional participants), were required, one for rating the target stimuli in terms of color complexity and the other for rating the same stimuli in terms of color symptomaticity. The participants serving in these groups received US$20 for their participation.

Materials

A set of 154 digitized color photos of common objects (e.g., bus, chair, scissors, elephant) was created, each cropped to a rectangle with 240 vertical and 320 horizontal pixels. Each object was then "cut-out" from its background, and superimposed on a circular white background disk with a 240-pixel diameter. The object in each photo was scaled to 220 pixels, corresponding to 6° of visual angle at the participants' viewing distance of 60 cm, and was centered on its background disk. We also produced a parallel set of 154 black and white photos by translating each digitized color photo to its black and white equivalent.

During the study and test phase, all pictures were displayed on a 15-inch Sony SF2 color graphics monitor with 1024 by 768 pixel resolution, driven by an ATI Mach 64 graphics engine operating in 16.7 million color mode. The presentation of all pictures was controlled by the PicBlit 2.6 software package (Uttl, 1992–97).

Of the 154 photos, 60 were critical targets, 84 were fillers, and 10 were used for instructions and practice. The 60 critical targets were randomly divided into 10 equal sized sets, identified as sets C1 to C10, each with six photos. Similarly, the 84 fillers were divided into 14 equal sized sets, here identified as F1 to F14. All objects that were used had a single dominant upright orientation.

Procedure

Identification testing and repetition priming. The experiment was described as examining perception of common objects. Participants were tested individually in a single session that lasted about 75 mins. They were seated at a desk about 60 cm from the computer monitor. The session had a study phase and a test phase. The study phase procedure was the same for all participants. On each trial, a picture, either a color or black and white photo of an object, was shown in the center of the computer monitor in one of the three display orientations, at 0°, 120° or 240° respectively. The participants' task was to rate how easy it was to identify each object. In order to make the ratings, participants used a three-point scale with the endpoints labeled as follows: 1 – difficult to identify to 3 – easy to identify. They responded by pressing the appropriate button on a three-button mouse. Participants practiced the rating task with eight different photos, proceeding at their own pace across trials. Each mouse press blanked the screen for 2–3 s and triggered the display of the next photo. Following the practice phase, a randomly-arranged list of 72 photos (six sets in black and white and six sets in color) was presented according to the same procedure. As shown in Table 2, for each subject, two subsets of each photo type (color or black and white) were displayed in each orientation condition (rotated 0°, 120°, and 240° in the plane of the page). Counterbalancing was used to ensure that across participants, all critical picture subsets appeared equally often in each study phase condition.

The identification test phase followed immediately after the study phase. For the test, each subject was presented with a random arrangement of 144 photos, either displayed in black and white or

Table 2. *An example of how photos were assigned for one participant on the color test*

Study photo type and orientation	Test orientation	Set	Study–Test change	
Color/120°	**120°**	$\mathbf{C_1}$	**S/O**	**S/C**
B&W/120°	**120°**	$\mathbf{C_2}$	**S/O**	**D/C**
Color/0°	**120°**	$\mathbf{C_3}$	**D/O**	**S/C**
B&W/0°	**120°**	$\mathbf{C_4}$	**D/O**	**D/C**
	120°	$\mathbf{C_5}$	**NEW**	
	120°	F_9		
	120°	F_{10}		
	120°	F_{11}		
Color/240°	**240°**	$\mathbf{C_6}$	**S/O**	**S/C**
B&W/240°	**240°**	$\mathbf{C_7}$	**S/O**	**D/C**
Color/0°	**240°**	$\mathbf{C_8}$	**D/O**	**S/C**
B&W/0°	**240°**	$\mathbf{C_9}$	**D/O**	**D/C**
	240°	$\mathbf{C_{10}}$	**NEW**	
	240°	F_{12}		
	240°	F_{13}		
	240°	F_{14}		
B&W/120°	0°	F_1		
Color/120°	0°	F_2		
B&W/240°	0°	F_3		
Color/240°	0°	F_4		
	0°	F_5	NEW	(Upright)
	0°	F_6	NEW	(Upright)
	0°	F_7	NEW	(Upright)
	0°	F_8	NEW	(Upright)

Notes: S/O denotes objects presented in the same orientation at study and test; D/O denotes objects presented in different orientations at study and test; S/C denotes objects presented in the same color at study and test; and D/C denotes objects presented in different colors at study and test. A parallel assignment of stimuli was used for participants who saw black and white photos at test. Critical conditions are printed in bold. Critical sets of objects are denoted by C and were counterbalanced across participants whereas fillers are denoted by F and were fixed across participants. Type of photo (black and white vs. color) at test was a between-subject variable.

in color. Of these photos, 72 were from the study list and 72 were new, that is, not from the previously shown list. We used the latter photos in order to obtain an estimate of baseline performance for each display orientation condition of the object identification test, as well as to ensure that an equal number of photos was displayed in each of the three display orientations. As indicated in Table 2, for each subject eight sets of fillers items were displayed in the 0° rotation condition, and three sets of fillers were displayed in the 120° and 240° rotation conditions, respectively. By this assignment of materials, we ensured that on the test the same proportion of items were old (studied) and new (non-studied).

The test was constructed so that for the items included in the study list, exactly one subset (six items) appeared in each of the eight critical test conditions: same color, same orientation and displayed at 120° different color, same orientation and displayed at 120° same color, different orientation and displayed at 120° different color, different orientation and displayed at 120° same color, same orientation and displayed at 240° different color, same orientation and displayed at 240° same color, different orientation and displayed at 240° and finally, different color, different orientation and displayed at 240°. Table 2 illustrates the manner in which the sets of critical and filler items were assigned to the critical study and test conditions for one participant who was in color object condition of the test phase. Across participants, counterbalancing ensured that each critical set of objects (sets C_1 to C_{10}) appeared equally often in each of the critical and baseline conditions of each test. The assignment of filler sets to conditions was the same for all participants.

On each trial of the identification test, a photo was displayed by means of a fade-in procedure and the participants' task was to identify each object as quickly and accurately as possible, to press the left mouse button as soon as they had identified it, and then to tell the object's name to the experimenter. The experimenter recorded participants' responses by typing them on the keyboard. Pressing the mouse button stopped the fade-in procedure, cleared the computer screen, and caused the display of a prompt for recording the name of the displayed object.

The fade-in procedure used in the present study is similar to the widely used picture fragment completion test used for many previous investigations of object identification and priming (e.g., Biederman & Cooper, 1991; Cooper *et al.*, 1992; Srinivas, 1996; Goodglass *et al.*, 1984). However, our procedure is more sensitive by virtue of the fact that it steps through 240 levels of fragmentation rather than only the six or seven that are typically used for a picture fragment completion test. Our fade-in procedure operated on the pixel map of each picture that was made up of 240 rows and 320 columns. The program stepped through all pixels turning them on in a random order without replacement (see Uttl & Graf, 1996, for more detail). The participant's response (i.e., a mouse button press) generated an interrupt that stopped the fade-in procedure, cleared the display screen, and recorded the number of pixels turned on prior to the mouse button press. The participants practiced the identification task with eight pictures, and then worked through the 144-item test list. A delay of 2–3 s (i.e., the time required to load the next picture into memory plus a brief delay) separated successive test items.

Color symptomaticity rating. A separate group of 15 participants rated all photos with respect to their color symptomaticity. Each was presented with an individually randomized list of all color photos, according to the same procedure used for the study phase of the experiment, except that all objects were displayed in their normal upright orientation. The participants were instructed to rate each photo in terms of how symptomatic each object's color is to its identity. They used a five-point scale for this purpose, with 1 meaning that "its color is not at all symptomatic of the object" and 5 meaning that "its color is very much symptomatic of the object".

Color complexity rating. An additional 15 participants rated the photos for color complexity, following the same basic procedure as for the color symptomaticity rating part of the experiment. For the color-complexity rating task, participants rated the complexity of each object's coloring on a five-point scale, with 1 meaning that the object is not at all color-complex (i.e., it has a single, uniform coloring) and 5 meaning that the object is color-complex (i.e., it has a complex pattern or arrangement of colors).

RESULTS

The critical dependent measure collected during the test phase was the percentage of pixels required for the identification of studied and non-studied black and white and color photos in each experimental and control condition. We screened the data for outliers, defined as values that differed by more than 2.58 standard deviations (corresponding to $p < 0.01$) from their condition mean. In order to reduce the influence of outliers on statistical analyses, outliers were set equal to the value of the largest or smallest non-outlier, respectively. The alpha level was set at 0.05 for all statistical tests.

Study phase identification ratings

During the study phase, subjects used a three-point scale to rate how easy or difficult it was to identify each displayed object. The analyses of the identification data showed that participants rated objects displayed in upright orientation ($M = 2.02$) as easier to identify than objects displayed in the 120° ($M = 2.13$) or 240° ($M = 2.14$) orientations. The results also showed that objects displayed in color ($M = 2.08$) were easier to identify than objects displayed in black and white ($M = 2.11$). An ANOVA of the identification ratings with display orientation (0°, 120°, 240°) and display color (black and white versus color) as within-subjects factors and test condition (black and white test versus color test) as between-subjects factors revealed a significant main effect for display orientation, $F(1, 138) = 28.68$, $MSE = 0.04$, $\eta^2 = 0.17$, $p < 0.001$, as well as a significant main effect for display color, $F(1, 138) = 9.76$, $MSE = 0.03$, $\eta^2 = 0.07$, $p = 0.002$. No other main or interaction effects achieved significance.

Test phase identification and priming of rotated objects

Preliminary analyses. Preliminary analyses showed that some photographed objects were often identified incorrectly, and others were difficult to identify. In order to reduce any biasing influences due to such objects, we excluded the data obtained from those identified correctly by fewer than 80% of participants, as well as from those whose identification required more than 80% of their pixels. After screening according to these criteria, the data from 54 out of a possible 60 critical photos remained available for analysis. Further screening revealed that participants made incorrect identifications (i.e., they stopped the fade-in procedure but then could not correctly identify the object) on 3.5% of the test trials (3.9% in the black and white test condition, 3.0% in the color test condition; 2.1% in the conditions where the study and test orientations were the same and 4.1% in the conditions where the study and test orientations were different; 3.1% in the conditions where the study and test colors were the same and 3.1% in the conditions where the study and test colors were different) and the data from these trials were also eliminated prior to the main data analyses. Thus, the results and analyses reported below are based on correct identification test responses only.

In the study and test phase of the experiment, objects were shown in three different display orientations: rotated by 0°, 120° or 240° in the plane of the page. However, as described in the Method section, the critical items were displayed in, and counterbalanced across, only the latter two conditions, that is, rotated either 120° or 240° in the plane of the page. A preliminary analysis showed that for the critical

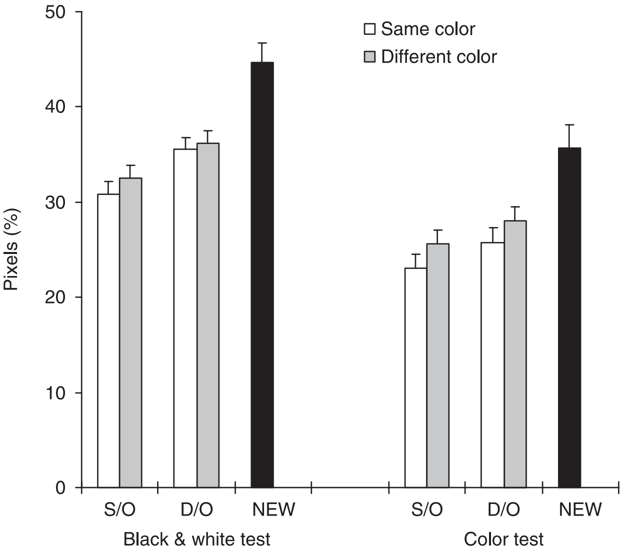

Fig. 1. Percentage of pixels required to identify each object as a function of photo type at test, photo type at study, study/test orientation condition (S/O = same orientation at study and test, D/O = different orientation at study and test), and history (studied vs. new). Extension bars represent 95% confidence intervals around each condition mean based on within subject error terms.

items, the test-phase display orientation (120° or 240°) did not affect performance either on new, non-studied or old, studied items. An ANOVA of identification performance on new, non-studied items with test phase display orientation (120° or 240°) as a within-subject factor and test condition (black and white versus color) as a between-subject factor revealed no significant main or interaction effect involving test phase display orientation. Similarly, an ANOVA of old, studied items with test display orientation (120° or 240°), study-test display history (same or different), and study-test color history (same or different) as within subjects factors and test condition (black and white versus color) as a between subject factor revealed no significant main or interaction effects involving test display orientation, largest $F(1, 138) = 1.66$, $p = 0.20$. For this reason, we combined the data across the two test display orientation conditions for all subsequent analyses.

Object color. Figure 1 shows the mean percentage of turned-on pixels that was required for correctly identifying photos in each experimental and control condition. The error bars represent the 95% confidence intervals around each mean, based on the within-subjects error terms (Loftus & Masson, 1994; Masson & Loftus, 2003). The means reveal that baseline identification, depicted by the black bars, was more difficult – a greater percentage of pixels had to be turned on for successful identification – with black and white photos (44.7%) than with color photos (35.7%) of objects. An ANOVA of identification performance on new, non-studied items with test type (black and white, color) as a between-subjects factor revealed a significant effect of test type, $F(1, 138) = 34.63$, $MSE = 2790$, $p < 0.001$.

The means also show that the percentage of pixels required for the identification of studied objects (29.7%), depicted by the lighter bars in Fig. 1, was substantially lower than the percentage of pixels required for the identification of non-studied objects (40.2%). The reduction in the percentage of turned-on pixels required for old, studied items versus new, non-studied items is due to priming, and the depicted data show a substantial amount of priming in each experimental condition.

We found more priming for objects displayed in the same orientation at study and test (12.2% of pixels) than for objects displayed in different orientations (8.8% of pixels), and overall more priming for objects displayed in the same color at study and test (11.4% of pixels) than for objects displayed in different colors (9.6% of pixels). An ANOVA with study-test orientation (same, different) and study-test color (same, different) as within subject factors and test type (black and white, color) as between subject factor revealed a significant main effect of study-test orientation, $F(1, 138) = 34.75$, $MSE = 45.04$, $\eta^2 = 0.20$, $p < 0.001$, and study-test color, $F(1, 138) = 18.75$, $MSE = 23.91$, $\eta^2 = 0.12$, $p < 0.001$. No other main or interaction effects approached significance.

A planned, complementary ANOVA focused only on the most critical conditions – the conditions where only color changed between study and test (i.e., S/O conditions in Fig. 1). The ANOVA of priming scores with study-test color (same, different) as within subject factors and test type (black and white, color) as a between subject factor revealed a significant main effect of study-test color, $F(1, 138) = 12.57$, $MSE = 25.69$, $\eta^2 = 0.08$, $p < 0.001$. No other main or interaction effects approached significance.

Color complexity. Based on the data provided by the 15 participants who made color complexity ratings, we computed an average complexity rating for each object and then divided the objects into two equal sets by means of a median split method. Next, we used these object sets to examine the effects of object color complexity on identification performance and priming.

Figure 2 shows performance on the object identification tests as a function of color complexity. The data summarized in Fig. 2 show that, overall, *color-simple* objects – those receiving the lower color complexity ratings and displayed in the top panel – were somewhat easier to identify (i.e., a smaller percentage of pixels was required for their identification – 37.1%) than *color-complex* objects (44.0%) – those receiving the higher color complexity ratings and displayed in the bottom panel. However, this difference between the object sets was not reliable. An ANOVA of the percentage of pixels required for identification of new, non-studied objects with color complexity (simple, complex) as between items factor and test type (black and white, color) as within-items factor revealed a significant main effect for test type,

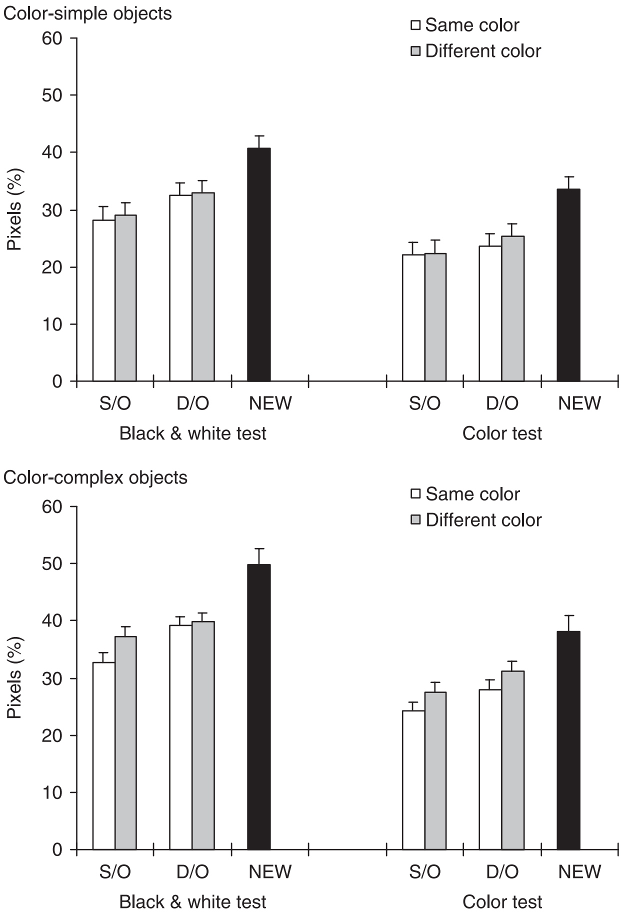

Fig. 2. Percentage of pixels required to identify objects as a function of color complexity. Extension bars represent 95% confidence intervals around each condition mean based on within subject error terms. The S/O denotes conditions where orientation was the same at study and test and D/O denotes conditions where orientation was different at study and test.

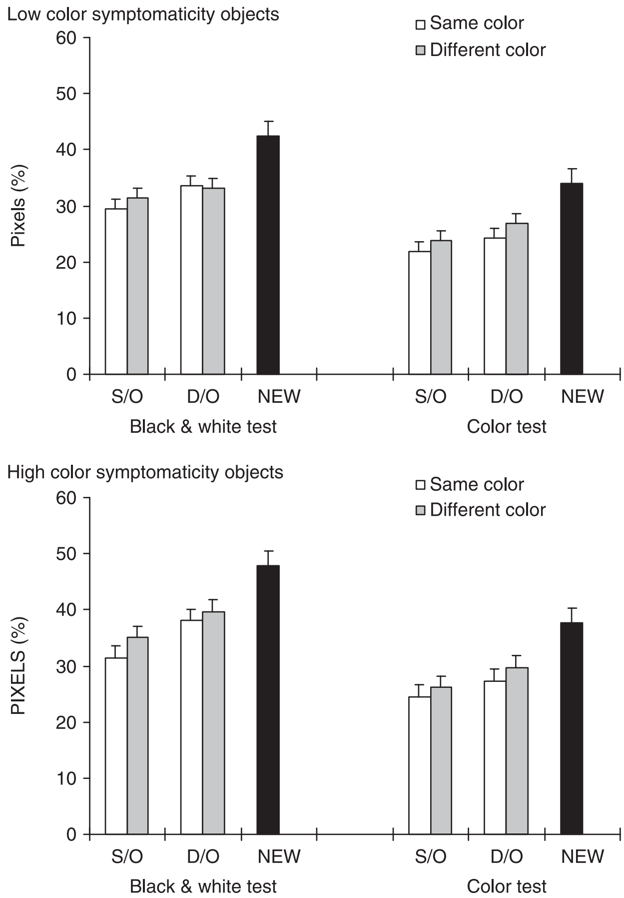

Fig. 3. Percentage of pixels required to identify objects as a function of color symptomaticity. Extension bars represent 95% confidence intervals around each condition mean based on within subject error terms. The S/O denotes conditions where orientation was the same at study and test and D/O denotes conditions where orientation was different at study and test.

$F(1, 52) = 61.44$, $MSE = 38.25$, $\eta^2 < 0.54$, $p < 0.001$, a marginal effect due to color complexity, $F(1, 52) = 2.98$, $MSE = 430.75$, $\eta^2 = 0.05$, $p = 0.090$, as well as a marginal interaction effect between color complexity and test type, $F(1, 52) = 3.70$, $MSE = 38.25$, $\eta^2 < 0.07$, $p = 0.060$.

The color-complex objects revealed a pattern of priming effects identical to that in Fig. 1: more priming for items displayed in the same orientation at study and test and more priming for items displayed in the same color at study and test. By contrast, the color-simple objects showed only a significant main effect for the study-test orientation (same, different) manipulation. An ANOVA of the priming scores with study-test orientation (same, different), study-test color (same, different), test type (black and white, color) as within-items factor and color complexity (simple, complex) as a between-items factor revealed significant main effects due to study-test orientation, $F(1, 52) = 47.58$, $MSE = 29.68$, $\eta^2 = 0.48$, $p < 0.001$, and study-test color, $F(1, 52) = 18.65$, $MSE = 20.81$, $\eta^2 = 0.26$, $p < 0.001$, as well as a significant color complexity by study-test color interaction effect, $F(1, 52) = 5.88$, $MSE = 20.81$, $\eta^2 = 0.10$, $p = 0.019$. No other main or interaction effects approached significance. Follow-up simple-effect analyses revealed a study-test color manipulation effect for color-complex objects, $F(1, 26) = 16.78$, $MSE = 28.21$, $\eta^2 < 0.39$, $p < 0.001$, but no such effect for color simple objects, $F(1, 26) = 2.78$, $MSE = 13.41$, $\eta^2 < 0.09$, $p = 0.107$.

Color symptomaticity. We used the data provided by the 15 participants who made color symptomaticity ratings, computed an average rating for each object and then divided the objects into two equal sets by means of a median split method. Next, we used the resulting object sets to examine the effects of object color symptomaticity by means of an item analyses.

Figure 3 shows object identification test performance as a function of color symptomaticity. The data summarized in Fig. 3 show that, overall, objects with lower color symptomaticity ratings were identified more easily (38.3% of pixels) than the objects with the higher ratings (42.8% of pixels), but this difference was not reliable. An ANOVA of the percentage of pixels required for identification of new, non-studied objects with color symptomaticity (low, high) as a between-items factor and test type (black and white, color) as a within-items factor revealed only a significant main effect due to test type, $F(1, 52) = 57.87$, $MSE = 40.61$, $\eta^2 < 0.53$, $p < 0.001$. No other main or interaction effect reached significance.

Overall identification performance and priming with both high and low color symptomatic objects showed the exact same pattern as that revealed by Fig. 1, thus suggesting that color-specific priming effects are not modulated by degrees of color symptomaticity. An ANOVA of the priming scores with study-test orientation (same, different), study-test color (same, different), test type (black and white, color) as within-item factors and color symptomaticity (low, high) as a between-items factor revealed significant main effects of study-test orientation, $F(1, 52) = 49.08$, $MSE = 28.77$, $\eta^2 = 0.49$, $p < 0.001$, and study-test color, $F(1, 52) = 17.03$, $MSE = 22.80$, $\eta^2 = 0.25$, $p < 0.001$. No other main or interaction effects approached significance.

Object origin. In a final analysis, we probed whether the object type, natural (e.g., animals, plants) versus fabricated (e.g., vehicles, furniture), had an influence on identification performance and on the pattern of priming effects. We divided the objects into two groups: natural (22 objects) and fabricated (32 objects) and examined the effects of object origin by conducting the item analyses reported below.

The top panel of Fig. 4 shows identification performance on the natural objects and the bottom panel shows performance on the fabricated objects. Overall, identification of natural and fabricated objects was equally easy (40.9% versus 40.3%). An ANOVA of the percentage of turned-on pixels required for identification of new, non-studied objects with object origin (natural, fabricated) as a between-items factor and test type (black and white, color) as a within-items factor revealed only a significant main effect of test type, $F(1, 52) = 57.40$, $MSE = 40.89$, $\eta^2 < 0.52$, $p < 0.001$. No other effects reached significance.

Overall identification performance with both natural and fabricated objects showed the exact same pattern of priming as that revealed by Fig. 1, thus suggesting that color-specific priming effects are not modulated by object origin. An ANOVA of priming scores with study-test orientation (same, different), study-test color (same, different), test type (black and white, color) as within-items factors and object origin (natural, fabricated) as a between-items factor revealed a significant main effect due to study-test orientation, $F(1, 52) = 45.21$, $MSE = 30.15$, $\eta^2 = 0.47$, $p < 0.001$, and study-test color, $F(1, 52) = 15.99$, $MSE = 23.16$, $\eta^2 = 0.24$, $p < 0.001$. No other main or interaction effects approached significance.

Identification of upright objects

In a final, supplementary analysis, we examined whether color influenced identification of upright objects (i.e., objects rotated 0° degrees). We analyzed identification performance on the four sets of filler items (24 objects, filler sets F_5 to F_8, see Table 2) that were not presented during the study but were presented to all participants on both the black and white and color tests. Preliminary analyses showed that one object was often identified incorrectly (more than 20% errors), and thus was excluded from the analyses (leaving a total of 23 fillers available for the analyses, 22 fabricated objects and one natural object). Further screening revealed that participants made incorrect identifications (i.e., they stopped the fade-in procedure but then could not correctly identify the object) on fewer than 3% of the test trials and the data from these trials were also eliminated.

The analysis of the remaining data from the upright filler items showed that a greater percentage of pixels had to be turned on for successful object identification with the black and white photos ($M = 39.7\%$, $SD = 7.89$) than with the color photos ($M = 34.1\%$, $SD = 5.70$). An ANOVA of the

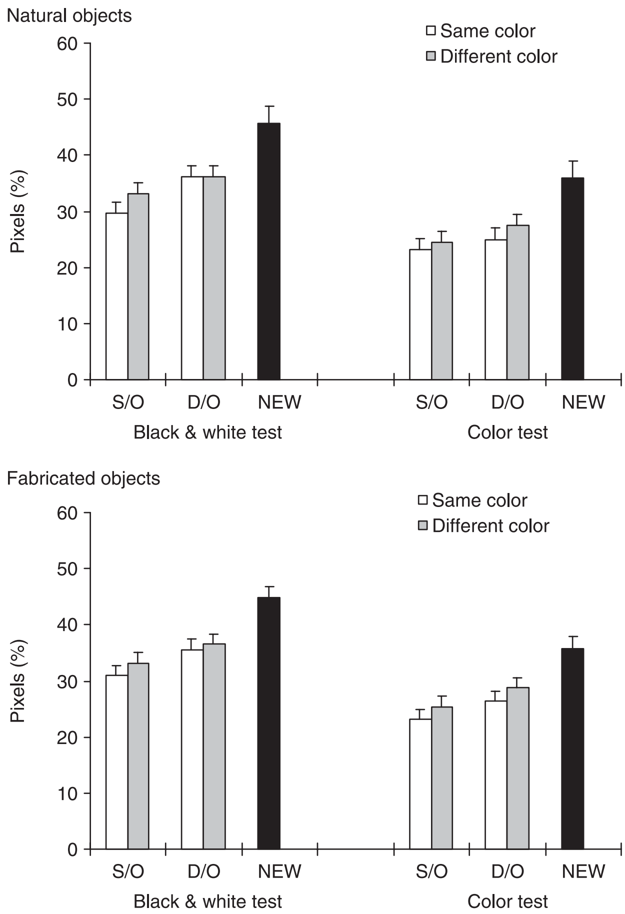

Fig. 4. Percentage of pixels required to identify objects as a function of object origin (natural vs. fabricated). Extension bars represent 95% confidence intervals around each condition mean based on within subject error terms. The S/O denotes conditions where orientation was the same at study and test and D/O denotes conditions where orientation was different at study and test.

percentage of pixels required for identification with test type (black and white, color) as a between subject factor revealed a significant main effect for test type, $F(1, 138) = 23.14$, $MSE = 47.39$, $\eta^2 = 0.14$, $p < 0.001$. Further analyses showed that this outcome was not due to a few aberrant objects; it seems to have been true for most items. We found a strong correlation between the percentage of pixels required for identification in the black and white and color test conditions ($r = 0.94$, $p < 0.001$), and we observed a color-test advantage on 20 out of 23 objects.

DISCUSSION

The primary goal of the present study was to investigate two related questions: Does the presence or absence of color information influence the identification of common objects and does it influence the magnitude of priming effects with such objects? The results give strong affirmative answers to both of these questions. We found that photographs of common objects that were presented for the first time were identified faster when they were shown in color rather than in black and white. The identification advantage produced by color information was substantial, averaging a facilitation effect of about 8.9% of pixels (effect size $d = 0.99$) for critical items that were displayed in a rotated orientation and an effect amounting to 5.6% of pixels for filler items that were displayed in upright orientation ($d = 0.82$). These findings are consistent with the outcome of the previous studies, listed in the first part of Table 1, which show a color-facilitation effect on the identification of objects. Our findings generalize the existing results to a new testing procedure; they show that color has a similar beneficial effect on the identification of both natural and fabricated objects, as well as on both color symptomatic and non-symptomatic objects. Our findings are consistent with the theoretical claim that color-information improves identification performance via low-level sensory and perceptual processes, by facilitating the detection of edges and primitive shapes (Biederman & Ju, 1988; Marr & Nishihara, 1978).

Our identification results suggest a possible explanation for why previous studies have frequently failed to find a color advantage that reached statistical significance. Many previous studies used color-simple or even achromatic objects and they displayed them either in "color" or in black and white. Biederman and Ju (1988), for example, included in their set of 29 target objects a substantial proportion that were achromatic (e.g., an old-fashioned black and chrome camera, an old-fashioned black rotary telephone), metallic (e.g., a nail, a fork), or otherwise "color simple" (e.g., a rolling pin, a lock). We believe this choice of objects may be responsible for the weak and unreliable color effects observed in prior studies.

Our identification test results contradict previous speculations that color facilitates the identification of only color symptomatic objects. This speculation was offered by Tanaka and Presnell (1999) who completed a study with 12 color symptomatic objects and 12 color asymptomatic objects, calling them high and low color diagnostic objects, respectively. In their Experiment 3, Tanaka and Presnell reported finding that color symptomatic objects were identified faster than color asymptomatic objects. However, a close inspection of their results (see Tanaka & Presnell, 1999, Appendix D) reveals that only 6 of their 12 color symptomatic objects showed a color advantage, with the remaining 6 showing a color disadvantage. Consistent with this evidence, therefore, Tanaka and Presnell's Experiment 3 findings may be more indicative of performance on a few specific items rather than reflecting a more general color symptomaticity effect. By contrast, our findings cannot easily be dismissed with the same criticism because they are based on a total of 54 objects (27 low and 27 high color symptomatic objects, respectively).

The novel and most important discovery of the present study is the finding of substantial color-specific repetition priming effects. Although several previous investigations (listed in the last section of Table 1) have revealed a priming advantage for objects that were displayed in the same color at study and test, these effects were typically small and not significant, except for one investigation (Wippich & Mecklenbrauker, 1998). In contrast, in the present study we found unambiguous evidence for a color-specific priming effect. This effect averaged about 15% across all conditions, but was consistently larger in the color than black and white test conditions, when objects were displayed in the same orientation at study and test rather than in different orientations, and for objects judged to be color-complex rather than color-simple.

In an attempt to explain the small color-specific priming effects observed in previous studies, a number of authors have speculated that such effects may occur with natural but not fabricated objects (e.g., Humphrey *et al.*, 1994). Our results do not support this speculation because we found very similar color-specific priming effects with both natural and fabricated objects.

We are not able to offer a definitive explanation for why our investigation succeeded in finding, where others have failed to find, substantial, significant color-specific priming effects with common objects. However, there are at least two non-exclusive possibilities. First, as pointed out above, many prior studies used color-simple or even achromatic objects. Our findings show that color specific priming effects tend to be minimal for color-simple objects but much larger for color-complex objects. Accordingly, it is possible that previous studies failed to find color-specific priming effects because they used color simple or achromatic objects. A second possibility, as outlined in the Introduction, is that the difference in outcomes may be attributable to the kind of objects used for the present versus previous investigations. In place of the object photographs we used, previous studies have employed outline drawings of such objects. We suspect that the outline drawing of an object is typically viewed as representing an object type rather than a token, that the identification of types and tokens may recruit different sensory/perceptual processes, and most importantly, that color-specific priming effects may be linked with the processes used for perceiving unique individuals. Consistent with these possibilities, Uttl and Graf (1996) found that overall priming effects were smaller for black-and white line drawings than for color photos of common objects.

The assumption that aspects of priming are linked with the perceptual processing of unique individual stimuli has been made previously to explain other repetition priming phenomena, notably the finding of long lasting priming effects with familiar words (e.g., Graf & Ryan, 1990) and objects (Cave, 1997). Previous research has shown that priming effects can last for very long periods of time, even for common words that are likely to be encountered outside the experimental situation during the retention interval (e.g., Kolers, 1975, 1976). It seems plausible that these long-lasting priming effects are mediated by representations that are unique to the episodic context in which items were encountered during the study and test phase of an experiment. We suggest that similar unique episodic representations may mediate color-specific priming effects with tokens but not types of common objects.

Another factor that may account for the different outcome between the present versus previous investigations is the manner in which color was manipulated between study and test. It may be that the outline of an object, whether drawn in one or another color, provides too little color information in order to significantly impact perceptual processing. An outline drawing unquestionably provides far less color information than does a color photograph. A future investigation will be required to examine whether this color-manipulation strength notion, the type versus token distinction discussed earlier, or a combination of these alternatives is responsible for the difference between our present findings versus those from previous studies.

Our finding of a color-specific priming effect with common objects parallels previous reports of priming effects specific to the spatial orientation in which objects were displayed for study and test (Uttl & Graf, 1996). Neither of these findings can be readily accommodated by models that explain priming effects in terms of abstract structural representations (e.g., Marr, 1982; Biederman, 1987; Tulving & Schacter, 1990; Schacter, 1994). One of the best known models of this kind is Biederman's recognition-by-components model which stipulates that objects are represented in terms of geons, basic geometric building blocks and special terms that define the relations between and among them. It is assumed that the perception of an object strengthens or cements its structural description – its representation in terms of geons and their relations, and in turn, this process facilitates the subsequent perception of the same object. However, neither the geons nor the relations among them are assumed to code specific color or other episodic information. Thus, if such effects are found, they must be attributed either to lower level sensory and perceptual processes (e.g., the detection of edges and shapes) or to higher-level processes.

Consistent with accounts offered by others, we have highlighted the role of low-level processes facilitating edge and shape detection, in order to explain the finding of a color advantage in the baseline condition (i.e., on objects that were presented for the first time in the experiment). Therefore, in order to explain any additional influences due to color information, that is color-specific priming effects, we could postulate that the study-phase processing of items primes such low-level processes. However, this route of influence seems improbable in part because low-level processes are not unique to individual objects; the same processes are likely to be recruited for different objects and thus there would be substantial interference among the representations of different objects.

Instead of low-level processes, previous investigators have focused on high-level processes to explain study-test phase specific influences on priming effects. For example, in agreement with Biederman (1987), Tulving and Schacter (1990) have postulated that the identification of and priming effects with objects are mediated by representations of their structural properties. In addition, however, they have also suggested that the structural description system is closely linked with the episodic memory system, and this system codes objects in terms of specific properties (e.g., color, spatial orientation, context) that are unique to each occurrence. Therefore, hybrid models like the one by Tulving and Schacter can accommodate our finding of color-specific priming effects by assuming that the identification of an object recruits both its structural descriptions as well as its episodic memory representations.

Instead of highlighting the contributions of potentially different representation systems (e.g., structural, episodic), other researchers have explained repetition priming effects in terms of instance representations (Craik, 2003; Feustel *et al.*, 1983; Graf & Ryan, 1990; Logan, 1988; Mandler, 1980; Rueckl, 2003; Uttl, Graf & Cosentino, 2003; Whittlesea, 2003). According to the latter views, each encounter with a stimulus engages a unique set of sensory and perceptual processes, and as a consequence, this same set of processes can be carried out more fluently in the future. The enduring consequences of processing an item are regarded as its episodic memory representation. Furthermore, it is assumed that when required to identify a familiar object, both newly formed (i.e., episodic memory representations) and preexisting (i.e., semantic memory representations) representations of the object are recruited for its identification, both of them influencing how the object is perceived and interpreted. The newly formed episodic representation will have a lesser influence on subsequent identification if an object already has many pre-existing representations in memory. By these views, identification is a dynamic process and that is shaped by a variety of object attributes including color. Both object identification and priming depend not only on a match between attributes present at study and test, but also on participants' familiarity with a specific view of the object, its coloring, the requirements of the study and test tasks which may focus attention either towards or away from processing specific attribute (e.g., color, orientation), and cues provided at test (which may include or exclude the specific attribute).

A consistent and substantial color-specific influence on priming with common objects complements previous research showing an orientation-specific effect on object priming (Tarr, 1995; Tarr, Bülthoff, Zabinski & Blanz 1997; Uttl & Graf, 1996). More importantly, this combination of findings strengthens the claim that priming effects with common objects are similar to the priming effects with written and spoken words, with names and faces. By highlighting the similarity in findings, the present study sets the stage for theory integration, and for abandoning theoretical accounts that are unique to one kind of material.

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