

The Contribution of Color to Object Recognition

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1. Introduction

The cognitive processes involved in object recognition remain a mystery to the cognitive sciences. We know that the visual system recognizes objects via multiple features, including shape, color, texture, and motion characteristics. However, the way these features are combined to recognize objects is still an open question. The purpose of this contribution is to review the research about the specific role of color information in object recognition. Given that the human brain incorporates specialized mechanisms to handle color perception in the visual environment, it is a fair question to ask what functional role color might play in everyday vision. Humans possess trichromatic color vision that most likely developed for specialized uses. For instance, color vision could be used to detect ripe fruit against a background of foliage (Gegenfurtner, 2003; Surridge, Osorio, & Mundy, 2003). Traditionally, theories of object recognition suggest that objects are recognized based on shape information, largely ignoring the role of color information (Biederman, 1987; Marr & Nishihara, 1978). However, more recently, a large body of behavioral, functional neuroimaging, and neurophysiological evidence suggests that color information make an important contribution to object recognition (for a review, see Tanaka, Weiskopf, & Williams, 2001). In the first part of this chapter we discuss the relevance of research on color effects in object recognition, while reviewing the neural mechanisms that support color perception. In the second part of the chapter we present a review of the literature exploring the color effects on object recognition and we discuss some apparently contradictory results described in the scientific literature. We also present the main results of a meta-analysis in which the behavioral literature on the effect of color in object recognition has been explored and integrated (Bramão, Reis, Petersson, & Faísca, 2011). In the third section, we review some of our own behavioral and electrophysiological data that might explain some of the conflicting results found in the literature, and we discuss the level at which color information might contribute to object recognition. We argue that the color effects in object recognition depend on the color diagnosticity status of the specific objects.

2. Color processing in the human brain

All mammals possess dichromatic or monochromatic color vision, but only primates have trichromatic color vision. What is the ecological advantage of having trichromatic color

vision? Primates evolved trichromatic vision from their dichromatic ancestors approximately 40 million years ago following the duplication of a gene coding for the L-cone (Jacobs, 1993; Jacobs & Rowe, 2004; Yokoyama, 2000). It is likely that color serve as a cue for object recognition; for example, animals may use color to assess the health of other members of their species; and color can aid image segmentation (Allen, 1879). But the dominant view is that trichromatic color vision emerged as a specific adaptation for finding fruits and young leaves against a background of mature leaves (e.g., Osorio & Vorobyev, 1996; Regan et al., 2001). This notion is particularly attractive, as many fruits gradually turn yellow, red or orange, and finally brown during ripening. These colors are strikingly visible to trichromats, but dichromats have difficulty distinguishing them from a dappled background of green leaves (**Figure 1**).



Fig. 1. The left image (A) shows in full color a picture of ripe fruit against a leafy background. To remove any advantage in seeing fruit conferred by trichromacy, (B) on the right side have had all the hue and saturation information removed, but are otherwise identical to image (A). The fruit in (B) is much less salient than in (A).

As the human brain evolved, it preserved the mechanism to handle color vision. Several physiological and anatomical studies have established the human color center in the V4 area located in the posterior part of the fusiform gyrus. However, this color center is a part of a more broadly distributed cortical network responsible for color processing, which includes V1, V2, V4, and regions beyond the inferior temporal cortex (e.g., Bartels & Zeki, 2000; Lueck et al., 1989; McKeefry & Zeki, 1997; Zeki & Bartels, 1999; Zeki et al., 1991). Nevertheless, it is unclear what role these brain regions play within the color processing system. Evidence suggests that the first stage of color processing, located in the V1 and V2, primarily registers the presence and intensity of different wavelengths. A second stage, located in the V4, is involved in automatic color constancy operations (Zeki & Marini, 1998). Color constancy is a property of the visual system that ensures that the perceived surface color remains relatively constant under varying illumination conditions. A very interesting case study reported by Zeki and colleagues (Zeki, Aglioti, McKeefry, & Berlucchi, 1999) shows the specific roles of V1, V2 and V4 within the color processing system. After an electric shock that led to vascular insufficiency, the patient PB became virtually blind, although he retained the capacity to perceive colors consciously. The psychophysical results suggested that color constancy were severely deficient in the patient and that his color vision was merely based on wavelength discrimination. Functional neuroimaging studies

showed that, when he viewed and recognized colors, significant increases in activity were restricted to V1 and V2, and no significant activation of V4 was observed. Finally, a third and final stage in color processing involves object colors. This is supported by the inferior temporal and probably also by the prefrontal cortex (Zeki & Marini, 1998). Little is known, however, about the neural mechanisms underlying higher-level aspects of color processing (cortical brain regions believed to be important for color perception are shown in **Figure 2**).

Given that the brain has developed specialized mechanisms to handle color perception information in the visual environment, it is a fair question to ask what functional role color might play in everyday vision, in particular in object recognition.

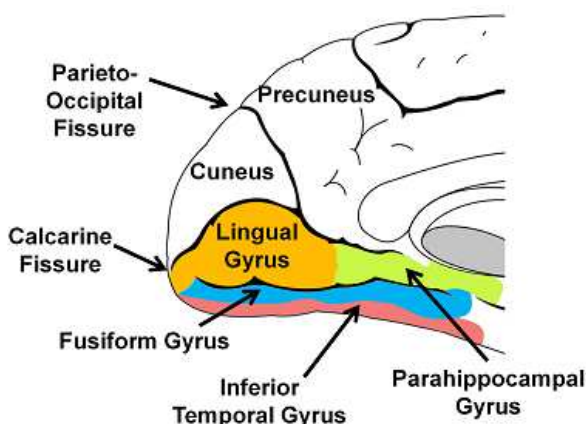


Fig. 2. Schematic view of the human brain. The regions that are important for various aspects of color perception are shown. These regions include the lingual gyrus and the posterior portion of fusiform gyrus, located below the calcarine fissure.

3. Does color information improve object recognition?

Traditionally, theories of object recognition suggest that objects are recognized based only on shape information, largely ignoring the potential role of color information (Biederman, 1987; Marr & Nishihara, 1978). For instance, in the recognition-by-components (RBC) model, proposed by Biederman (1987), objects are described as spatial arrangements of a restricted set of roughly 30 basic component shapes, such as wedges and cylinders, called geons. This idea suggests an analogy with words, which are constructed from a restricted set of phonemes. Biederman (1987) suggested that the first stage of object recognition involves the segmentation of the contour in regions of sharp concavity. This segmentation divides the contour into a number of parts that then are matched against the set of geons. Biederman (1987) used view-invariant representations. According with the RBC model, geons are defined by properties that are invariant over different views. Object representations are simply assemblies of geons constructed by inferring the qualitative spatial relations between them. Because geons and the relationships between them are viewpoint-invariant, the recognition process is likewise viewpoint-invariant. One strong point of this theory is the fact that geons are not only view-invariant, but also to other surface properties, such as size, color or texture.

However, more recently, a large body of behavioral, neuroimaging and neurophysiological studies suggest that color might contribute to object recognition. Tanaka and colleagues (Tanaka, Weiskopf, & Williams, 2001) proposed the “Shape + Surface” model of object recognition that takes into consideration the recent evidence for the role of color information in object recognition (**Figure 3**). The model recognizes that object recognition is primarily a shape-driven system (e.g., blue strawberries are still recognized as strawberries); however, color and possibly other surface properties, such as texture, are perceptual inputs for the object representation system. The Shape + Surface model draws a distinction between surface color at the input level and stored color knowledge and considers object recognition to be jointly determined by the bottom-up influence of surface color and the top-down influence of color knowledge. According to this model, visual color knowledge can be triggered either by the perceptual object during object recognition or by its lexical label during mental imagery. Finally, the model maintains a separation between linguistic and visual representations of object color. For example, it is possible to know that strawberries are red without having to consult a visual representation.

By examining whether there is an advantage to recognizing the typical colored version of an object (e.g., a red strawberry) over its black and white or atypical color version (e.g., a purple strawberry), it is possible to verify whether color information contributes to object recognition. However, this relatively straightforward test has yielded mixed results. Some studies have shown that recognition times are essentially unaffected by color information (Biederman & Ju, 1988; Davidoff & Ostergaard, 1988; Ostergaard & Davidoff, 1985). However, other studies have found that objects presented in their typical color version are recognized faster than when individuals are presented with their black and white or atypical color versions (e.g., Humphreys, Goodale, Jakobson, & Servos, 1994; Price & Humphreys, 1989; Theriault, Yaxley, & Zwaan, 2009; Wurm, Legge, Isenberg, & Luebker, 1993).

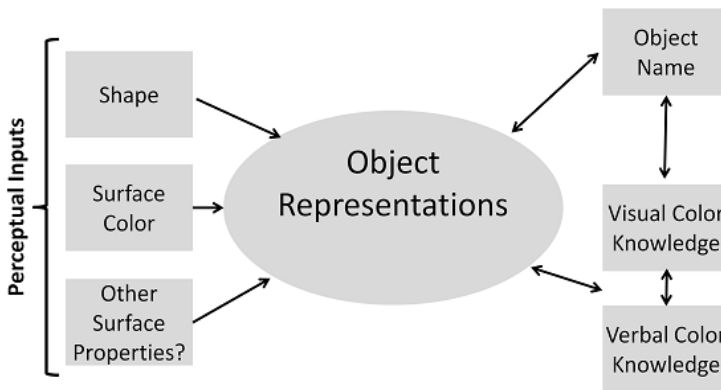


Fig. 3. The Shape + Surface model of object recognition. Adapted from Tanaka, Weiskopf and Williams (2001).

Different explanations have been proposed for these apparently contradictory results. For instance, color information may facilitate the recognition of objects within structurally similar categories (e.g., animals, fruits) but not structurally dissimilar categories (e.g., body

parts, musical instruments, tools). Objects belonging to structurally similar categories activate a larger set of structural representations, leading to a higher competition within the visual system, and thus color can help resolve this competition (Price & Humphreys, 1989). Other studies have proposed that color can provide useful information when objects are high color diagnostic objects, that is, when objects are strongly associated with a color (Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999). For example, a color diagnostic object, such as a strawberry, is strongly associated with the color red. A comb, however, which is a non-color diagnostic object, is not strongly associated with any particular color.

In a recent meta-analysis we systematically review the scientific literature on the effect of color information on object recognition (Bramão, Reis, Petersson, & Faisca, 2011). Thirty-five independent experiments, comprising 1535 participants, were included in this meta-analysis. Overall, we found a moderate significant effect of color on object recognition ($d = 0.28$, $p < 0.001$), establishing in that way that color information plays a role in object recognition and should be considered in the visual object recognition models (Figure 4).

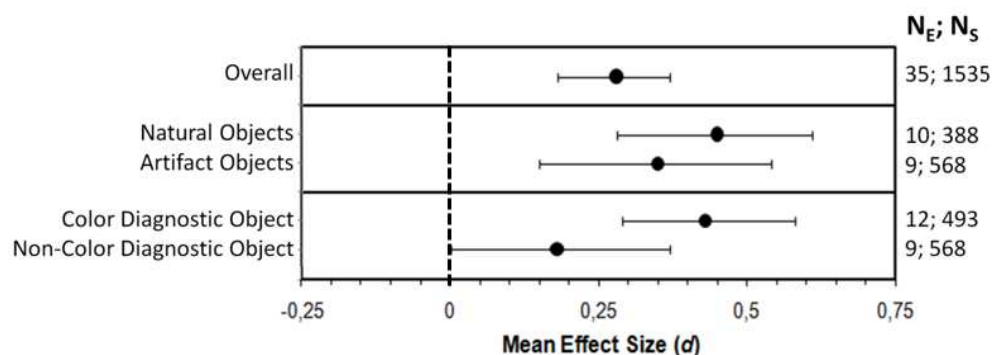


Fig. 4. Mean effect size (d) and 95% confidence intervals. The moderator variables tested in specific meta-analytic comparison are labeled on the left side. Labels to the right side of the figure indicate the number of independent effect sizes (experiments) which contributed to each meta-analysis (N_E), and the number of subjects these effect sizes were based upon (N_S). Adapted from Bramão, Reis, Petersson and Faisca (2011).

Additionally, we tested the specific moderator effect of a series of potential moderator variables on the role of the color information during object recognition (e.g., *stimuli type*, *object recognition task*, etc...). Here, we just present the results concerning the *object's semantic category* and *color diagnosticity* (for the complete analysis, see Bramão, Reis, Petersson, & Faisca, 2011). The impact of color in the recognition of objects from different semantic categories was first addressed by Price and Humphreys (1989). The authors found that object naming was facilitated by color when objects were from natural categories. Because objects from natural categories tend to be more structurally similar than artifacts, the competition within the object recognition system is greater for natural objects, and color information appears to be an important cue in resolving this competition. Wurm and colleagues (Wurm, Legge, Isenberg, & Luebker, 1993) showed that prototypical images exhibit a smaller color advantage compared to non-prototypical images. These observations led to the idea that color plays an important role in object recognition when shape is not

diagnostic or typical. Moreover, the observed color advantage for natural objects might be related to the fact that they are typically strongly associated with a specific color and therefore, their color tends to be more diagnostic compared to artifacts. This interaction between category and color diagnosticity was addressed by Nagai and Yokosawa (2003), who reported a color advantage for high color diagnostic objects regardless of their category. Corroborating this idea, other studies have reported a similar color advantage for natural objects and artifacts (Bramão, Faisca, Forkstam, Reis, & Petersson, 2010; Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). Our meta-analysis also supports the idea that color is important for the recognition of objects from both categories: we observed that color facilitates the ability to recognize both natural ($d = 0.45, p < 0.001$) and artifact objects ($d = 0.36, p < 0.001$) (Figure 4; Bramão, Reis, Petersson, & Faisca, 2011).

Color diagnosticity, however, showed a great moderator effect on the influence of color on object recognition: studies using color diagnostic objects showed a significant color effect ($d = 0.43, p < 0.001$), whereas a marginal color effect was found in studies that used non-color diagnostic objects ($d = 0.18, p = 0.06$) (Figure 4; Bramão, Reis, Petersson, & Faisca, 2011). Color diagnosticity is probably the most investigated property in studies exploring the role of color information in object recognition. According to the color diagnosticity hypothesis, color diagnostic objects are the most likely candidates to show an advantage due to color information in object recognition tasks (Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999). For example, Tanaka and Presnell (1999) showed that the presence of color information has a significant impact on the recognition of high color diagnostic objects and no effect on the recognition of objects with low color diagnosticity. In a control condition, when high and low color diagnostic objects were matched for structural complexity, reliable color effects were still found, suggesting that color made a unique contribution to recognition in a manner that is independent of shape. Similar results were found in the recognition of everyday scenes (Oliva & Schyns, 2000). Scenes that are rich in color diagnostic content (e.g., coast, forest) are best recognized in their typical color versions when compared to black and white or atypical color versions. On the other hand, non-color diagnostic scenes (e.g., city, shopping area) showed no difference in recognition performance across the typical, black-and-white and atypical color versions (Oliva & Schyns, 2000). Thus, the concept of color diagnosticity generalizes to the recognition of both objects and scenes.

However, recent studies have failed to replicate this finding and have documented that color information, independent of the color diagnosticity status of the object, improves its recognition (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). For example, Rossion and Pourtois (2004) colored the 260 line-drawings from the Snodgrass and Vanderwart (1980) set with texture and shadow details. Norms for the color diagnosticity level of the objects were collected and correlated with the advantage provided by color alone in the naming responses. The authors did not report a significant correlation between these two measures ($r = 0.05$), showing that color information improves object recognition independently of its color diagnosticity level.

The interactions between color diagnosticity and the observed advantage due to color information are not well understood, and the reasons for the apparently contradictory results reported in the literature are not obvious. One possibility is that color information helps the recognition of color and non-color diagnostic objects at different levels of visual

processing. To recognize an object, different processing stages must be resolved (Humphreys, Price, & Riddoch, 1999). First, the perceptual input must be encoded and matched against a template form stored in the long-term memory. Next, the semantic object representations are accessed, and, finally, the object name is activated. Color information might be useful for recognition of both color and non-color diagnostic objects in the early stages of the visual processing. Specifically, this information could be used to match the perceptual input with a known shape representation or, at an even earlier visual processing stage, segregate and organize the visual input. However, in the later stages of the recognition process, color information might play different roles depending upon the color diagnosticity status of the specific objects. Although color information might be important for semantic representation of a color diagnostic object, color information is probably not as important for semantic representation of a non-color diagnostic object. When we think about the properties of a strawberry, the property red is one of the first that comes to mind; however, if we think about the features of a comb, its color is not one of the first properties one might think of. Thus, we proposed that color information might participate in the recognition of color and non-color diagnostic objects at different levels of visual processing. More specifically, we hypothesize that color information participates in the recognition of both types of objects in the early visual perceptual stages, helping both segmentation and organization of the perceptual input. Studies have indicated that color information is an important cue in the early visual processing stages (Gegenfurtner & Rieger, 2000; Wurm, Legge, Isenberg, & Luebker, 1993); however, these studies did not control for or manipulate the color diagnosticity level of the presented objects. Color information is expected to play an additional role during the recognition of color diagnostic objects at the semantic levels of visual processing. Color is an intrinsic property of these objects. For example, Naor-Raz and Tarr (2003), using a variation of the Stroop paradigm, asked participants to name the displayed color of objects and words. They found that color is an intrinsic property of color diagnostic objects at multiple levels. Thus, the presence of color information in an image of a color diagnostic object might be important for the activation of semantic object representation and recognition of the object.

4. The influence of color information on the recognition of color diagnostic and non-color diagnostic objects

In this section we present the results from two studies that aimed to clarify the conflicting results found in the literature and to test the hypothesis that the color effects in object recognition depend on the color diagnosticity status of the specific objects. More specifically, we hypothesize that color information influences the recognition of both color and non-color diagnostic objects at the low-level of vision (e.g., improving the segmentation and the organization of perceptual input). However, color is expected to play an additional role in the recognition of color diagnostic objects at higher levels of the visual processing.

In a first study, participants performed three object recognition tasks with different cognitive demands at the perceptual, semantic and phonological levels: an object verification task, a category verification task, and a name verification task. Humphreys and colleagues argued that performance of these tasks poses different challenges for the cognitive system (Humphreys, Price, & Riddoch, 1999; Humphreys & Riddoch, 2006; Humphreys, Riddoch, & Quinlan, 1988; Riddoch & Humphreys, 1987). In the name

verification task, participants were instructed to verify the name of visually presented objects. A number of processing stages must be completed before accessing the name representation. First, the early visual processes must encode the object shape and other perceptually available information. The encoded information must then be matched with the structural descriptions stored in long-term memory. The stored semantic and conceptual information about the object must be activated, and subsequently, the name representation is accessed. During this process, different forms of stored memory must be accessed, including knowledge about the object's shape (structural description), its functional and other meaning-related properties (semantic representation), and its name (lexical representation). In the category verification task, participants were instructed to verify the object's semantic category (natural or artifact). In contrast to name verification, category verification only depends on access to the stored structural description and the semantic representation. In the object verification task, participants were instructed to verify whether the presented object was a known object, and this only requires access to the structural description (Humphreys, Price, & Riddoch, 1999; Humphreys & Riddoch, 2006). By comparing the performance on these tasks, using both colored and black-and-white images, we attempted to determine the processing level at which color information facilitates the recognition of color and non-color diagnostic objects (**Figure 5**). If color information improves the recognition of color diagnostic objects both at the early visual and the semantic levels, then we expect to find an effect of the perceptual color for these objects when the task requires access to the structural description (i.e., in object verification). Furthermore, a larger effect of color information is to be expected for color diagnostic objects when the task requires access to both structural descriptions and semantic representations (i.e., in category verification). In the name verification task, we predicted color effects similar to those in the category verification task, given that no specific role of color is expected for accessing the lexical representation (i.e., the name) of an object *per se*. However, if color only modulates non-color diagnostic object recognition at the early visual processing stages, then we expect to find a perceptual color effect when the task requires access to the structural descriptions (i.e., in object verification). Moreover, we predicted that the perceptual color effect would remain constant for these objects on the remaining tasks, suggesting that only the early visual processing stages are affected by color information for these objects (Bramão, Inácio, Faísca, Reis, & Petersson, 2011).

In another study, we used ERPs to investigate this question. In contrast to behavioral measures, the ERPs permit the analysis of cognitive processes with a temporal resolution of milliseconds and represent an optimal approach to study the level at which visual processing of color information modulates object recognition. In a recognition task, subjects were presented with color and black-and-white versions of color and non-color diagnostic objects (**Figure 5**). Color effects were investigated in two early visual ERP components, the P1 and N1, and in two visual ERP components modulated by higher visual processes, the N350 and N400 (Bramão et al., Submitted). The P1 is an early scalp-recordable response to presented visual stimuli, which peaks at approximately 100 ms following stimulus onset and is best represented over the occipital sensors. This component has been associated with low-level visual processing but is also sensitive to attention (Mangun & Hillyard, 1991). The P1 is followed by a negative deflection peaking approximately 150 ms after stimulus onset termed N1, which has been observed primarily over the occipito-temporal region, and is an

electrophysiological index of perceptual processing, where increased visual processing demands are reflected in more negative values (Johnson & Olshausen, 2003; Kiefer, 2001; Rossion et al., 2000; Tanaka, Luu, Weisbrod, & Kiefer, 1999; Wang & Kameda, 2005; Wang & Suemitsu, 2007). Based on our previous research, we predicted that the ERP associated with black-and-white stimuli would elicit a more positive P1 response and a more negative N1 response in occipital sites compared to color stimuli for both color and non-color diagnostic objects recognition.

The late visual N300 and N400 components are ERPs related to semantic processing. N300 is a negative ongoing component that peaks at approximately 300 ms after stimulus presentation and has an anterior topographic distribution (Barrett & Rugg, 1990; McPherson & Holcomb, 1999; Pratarelli, 1994). The N300 appears specific for visual stimuli and reflects a neural system that supports object model selection and generic memory. The N300 is the earliest marker of successful object categorization, with increased negative magnitude over frontal regions for unidentified objects compared to correctly-categorized stimuli (Hamm, Johnson, & Kirk, 2002; McPherson & Holcomb, 1999; Schendan & Kutas, 2002, 2007). The N300 is followed by the N400 component, which is a negative deflection over central-parietal regions peaking at approximately 400 ms after stimulus onset. The N400 is widely used as an index of semantic processing, with an increase in negative magnitude for semantically unrelated compared to semantically related material (Kutas & Hillyard, 1980a, 1980b). Both the N300 and N400 ERP components are related to late visual processing, with the N300 reflecting early object categorization (e.g., activation of object structural features that lead to a categorical representation), and the N400 being sensitive to information extracted after initial categorization (Hamm, Johnson, & Kirk, 2002). According to our expectations, we predicted that color effects in these two components would be restricted to color diagnostic objects.



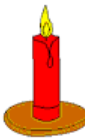



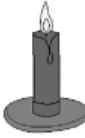

	Color Diagnostic Object		Non-Color Diagnostic Object	
	Line Drawing	Photograph	Line Drawing	Photograph
Color				
B&W				

Fig. 5. Example of the stimuli used in our experiments.

Our behavioral results showed that, during non-color diagnostic object recognition, the role of color was restricted to tasks that required high visual perceptual demanding. During

color diagnostic object recognition, however, color was found to play a role in tasks that required high semantic processing (**Figure 6**; Bramão, Inácio, Faisca, Reis, & Petersson, 2011).

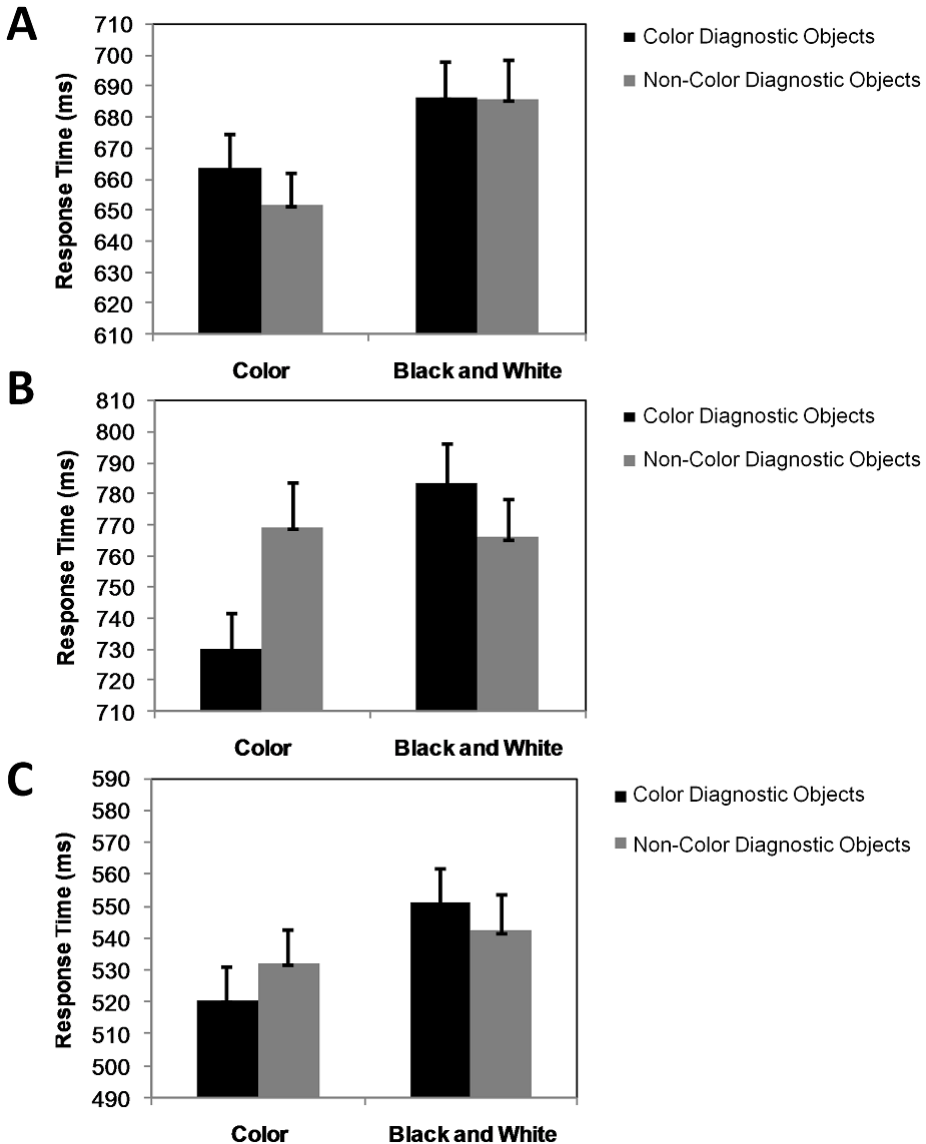


Fig. 6. Three-way interaction between the factors task, diagnosticity color object and presentation mode on verification times. A - Object verification task, B - Category verification task, C - Naming verification task. Bars represent standard error (Bramão, Inácio, Faisca, Reis, & Petersson, 2011).

The electrophysiological results corroborate our behavioral results. Independent of the color diagnosticity status, an early color effect was found (~100 ms after stimulus onset), suggesting that color aids image segmentation, thus lowering the visual demand of early visual processing stages. For color diagnostic objects, color effects occurred later (~350 ms after stimulus onset). These later color effects indicate that color is involved in the later stages of the recognition process for color diagnostic objects (Figure 7; Bramão et al., Submitted).

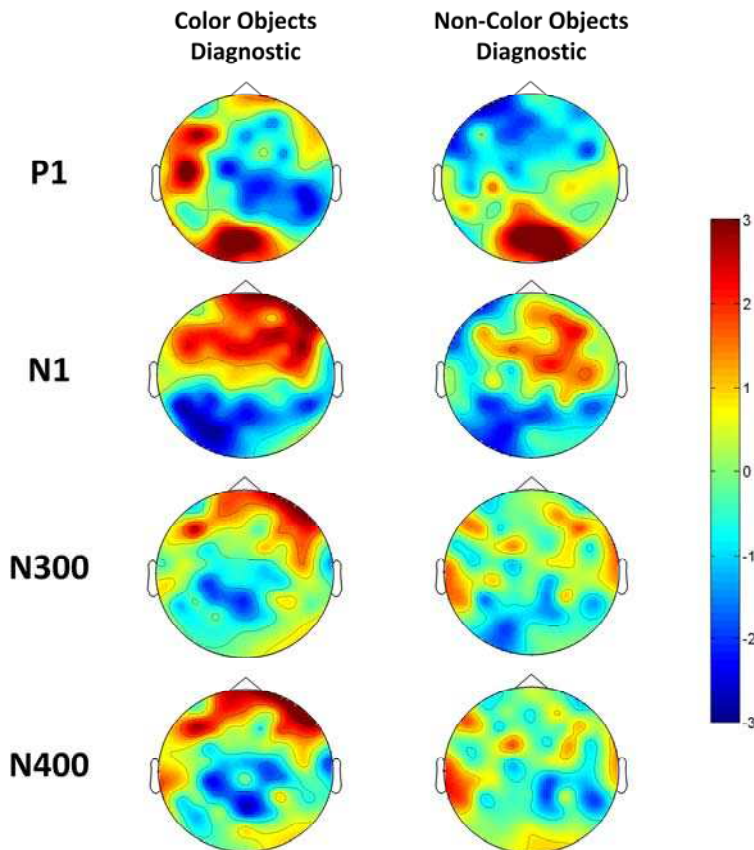


Fig. 7. Topographic distribution of the black-and-white *vs.* color objects in the time windows of interest for the color diagnostic and non-color diagnostic objects (Bramão et al., Submitted).

All together, these results suggest that color information contributes to the recognition of both color and non-color diagnostic objects but at different stages of visual processing. Color information has proven to be an important cue for solving the early perceptual demands at the initial stages of visual processing for both types of objects. Moreover, for color diagnostic object recognition, color information also contributes in the later stages of the visual processing.

The major outcome of these studies is that the influence of color on object recognition depends on object diagnosticity status. Tanaka and Presnell (1999) proposed that color information contributes to object recognition only when objects are color diagnostic (see also, Nagai & Yokosawa, 2003; Oliva & Schyns, 2000). However, recent studies have reported results that suggest that color contributes to the recognition of both color and non-color diagnostic objects (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). We have provided data that may clarify these apparently contradictory results. Our studies suggest that color information affects different levels of visual processing during the recognition of color and non-color diagnostic objects. For the recognition of non-color diagnostic objects, color information is an important cue for the initial image segmentation and visual input organization, making the selection of a structural description, stored in the long-term visual memory, easier and faster, thus resulting in faster object verification. Moreover, our results also show an absence of color effects for non-color diagnostic objects in the later stages of the visual process. However, for color diagnostic objects, we observed an additional role for color information. Beyond the facilitation that color information confers on the initial visual stages, our results showed a strong color effect in the later stages of object recognition. It appears that color affects the later stages of recognition of color diagnostic objects in two different ways. First, color information triggers the selection of the structural object description from long-term visual memory. When we see an object, color and shape are likely processed in a parallel fashion. Some studies suggest that the same neural circuits, in early visual cortical regions, process information about color, shape and luminance (Gegenfurtner, 2003). At some point, this information must be combined to achieve a unitary representation of the visual world. One possibility is that this information is combined during the selection of structural description, where color might act as a cue that limits the range of candidate structural descriptions. The results also suggest that the templates corresponding to color diagnostic objects are stored in our visual memory system in a typical color format. Second, color information contributes to the activation and retrieval of the semantic network associated with these objects.

5. Conclusions

Previous research has established a role for color information in the early and late visual processes of object recognition. However, many of these studies did not control for the color diagnosticity status of the objects or investigated only high-color diagnostic objects (Davidoff, 1991; Davidoff, Walsh, & Wagemans, 1997; Gegenfurtner & Rieger, 2000; Goffaux et al., 2005; Lu et al., 2010; Wurm, Legge, Isenberg, & Luebker, 1993). For example, Davidoff (1991) proposed a model of object recognition where color contributes to object recognition in the later stages of the visual processing. In this model, the author proposed the existence of two separate representations, one for object structure and another for object function, termed *has-a* and *is-a* representations, respectively. Object color, according to this model, is part of the *has-a* properties, so that recognition of an object's color takes place after the initial visual representation has accessed the *has-a* color knowledge. The absence of color at the stored object structure was first questioned by Price and Humphreys (1989). Price and Humphreys (1989) argued that there are separated representations for color and shape, but that these representations are richly interconnected and that appropriated color objects activate color representations that in turn activate associated shape representations (Humphreys et al., 1994; Price and Humphreys, 1989). Actually, the data presented in this

work shows that the role of color in object recognition depends on the correlation between color and shape. When the correlation between color and shape is high, as it is in the case of the color diagnostic objects, color information is especially important at the semantic representation level, whereas when the correlation between color and shape is low, as it is in the case of the non-color diagnostic objects, color information improves object recognition only at the early stages of the visual processing. These results suggest that color improves object recognition in the early stages of the visual processing for all objects. However, because non-color diagnostic objects are not strongly associated with a color, no further color advantage is expected at the higher processing levels.

The results reviewed in this contribution advance our current understanding of the role of color information during object recognition and its relationship with the object's color diagnosticity status. Together our results showed that color modulates the recognition of color and non-color diagnostic objects at different levels of visual processing: for color diagnostic objects, color plays an important role at the semantic level; for non-color diagnostic objects, color plays a role at the pre-semantic recognition level.

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An invariant object recognition system needs to be able to recognise the object under any usual a priori defined distortions such as translation, scaling and in-plane and out-of-plane rotation. Ideally, the system should be able to recognise (detect and classify) any complex scene of objects even within background clutter noise. In this book, we present recent advances towards achieving fully-robust object recognition. The relation and importance of object recognition in the cognitive processes of humans and animals is described as well as how human- and animal-like cognitive processes can be used for the design of biologically-inspired object recognition systems. Colour processing is discussed in the development of fully-robust object recognition systems. Examples of two main categories of object recognition systems, the optical correlators and pure artificial neural network architectures, are given. Finally, two examples of object recognition's applications are described in details. With the recent technological advancements object recognition becomes widely popular with existing applications in medicine for the study of human learning and memory, space science and remote sensing for image analysis, mobile computing and augmented reality, semiconductors industry, robotics and autonomous mobile navigation, public safety and urban management solutions and many more others. This book is a "must-read" for everyone with a core or wider interest in this "hot" area of cutting-edge research.

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