The Contribution of Color during Object Recognition: Behavioral, Electrophysiological and Neuroimaging Evidence

O Papel da Cor no Reconhecimento Visual de Objectos: Um Contributo de Estudos Comportamentais, Electrofisiológicos e de Neuroimagem

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Abstract

In this thesis, we present six studies that investigated the role of color information during visual object recognition. The interactions between surface color and color knowledge information were investigated in two studies (chapters 2 and 3). In chapters 4 and 5, we present data that identify the visual processing stage at which color information improves color and non-color diagnostic object recognition. In chapter 6, the neural pathways supporting color object recognition were investigated. Additionally, in an attempt to bring some consistency to the literature, we performed a systematic meta-analysis on the effects of color on object recognition in chapter 7.

Chapter 2 and 3 provided data suggesting that surface color information is more influential than color knowledge information during object recognition. Chapter 4 and 5 showed that color information improves the recognition of color and non-color diagnostic objects at different stages of visual processing. Although color information is an important cue for both of these types of objects in the early visual processes, it is also important in later stages of visual processing for color diagnostic object recognition. In chapter 6, we observed that colored objects, when compared with black and white objects, activated a more extensive brain network related to visuo-semantic activation and retrieval. Finally, the meta-analysis in chapter 7 conclusively showed a significant effect of color information during object recognition.

In summary, the general picture that emerges from this body of work is that color information takes part in object recognition processes at multiple levels of representation.

Keywords: surface color information, color knowledge information, color diagnostic objects, non-color diagnostic objects, object recognition and identification.

Chapter 1

General Introduction

1.1 Overview

The cognitive processes involved in object recognition remain a mystery to the cognitive sciences. The visual system recognizes objects via multiple features. The effortless way in which features are constructed to recognize objects seems to be almost magic. Color is one of the features of the environment that our visual system can extract and use. Humans possess trichromatic color vision that most likely developed for specialized uses. For example, color vision could be used to detect ripe fruit amongst foliage (Gegenfurtner, 2003; Surridge, Osorio, & Mundy, 2003). This thesis attempts to clarify the functional role of color information during object recognition processing.

The first models of object recognition emerged in the field of cognitive psychology 35 years ago. Although there is evidence to support the hypothesis that color information participates in object recognition, there is still no consensus regarding the type of objects and the viewing conditions that are affected by this visual attribute. This thesis outlines six studies that were designed to further elucidate the way in which color and shape information are combined to recognize familiar objects. In chapters 2 and 3, we clarify the interactions between surface color and color knowledge information during object recognition. In chapter 4 and 5, we investigate the visual processing level at which color participates in the recognition of color and non-color diagnostic objects. Chapter 6 presents the neural correlates associated with the recognition of colored objects. Finally, in chapter 7, we perform a meta-analysis on the effects of color on object recognition.

Before turning to the results of these studies, the themes that are relevant to the topics that are discussed in this thesis will be shortly introduced. First, we will briefly introduce the major models of object recognition and its neural basis. Next, we will present the current state of the art concerning the role of color information in object recognition.

1.2 Visual Object Recognition

Object recognition is an amazing human ability. We can effortlessly recognize and identify the objects around us within a fraction of a second. If we assume that the only information available to recognize the objects is a static two-dimensional image on the retina, a problem immediately arises in the explanation of visual recognition. Depending on the angle, lighting conditions and distance, there are an infinite number of possible retinal images that can correspond to a particular object, yet object recognition is enormously flexible and largely unaffected by these dramatic changes in object appearance.

In a pioneering study, Thorpe and collaborators (Thorpe, Fize, & Marlot, 1996) allowed observers only 20 milliseconds to determine whether an animal was present in a natural scene. Event-related potentials (ERPs) measured during the performance of this task revealed that, approximately 150 milliseconds after stimulus onset, there was a significant difference between the neural responses for trials in which there was an animal and trials in which there was not. Such data indicate that the visual system processes complex natural scenes quite rapidly and with only the briefest of inputs. Not surprisingly, how the human brain enables this to happen is currently an open problem for cognitive neuroscience.

Object Recognition Models

Most of the significant work in theorizing about object recognition came from Marr and Nishihara (1978), which was further developed a few years later by Biederman (1987). Marr and Nishihara (1978) developed a computational theory to explain how the human visual system recognizes an object. The authors introduced the idea of structural representations based on three-dimensional volumes and their spatial relations. In particular, they proposed that objects can be described as a set of generalized cones. A generalized cone is the surface created by moving a cross-section of constant shape but with variable size along an axis. Shapes that are elongated or that have a natural axis are more easily described in terms of generalized cones, and Marr and Nishihara (1978) limited their investigation to these types of objects. Generalized cones include forms such as spheres or cubes but can also include arms and legs. These powerful representational units have the potential to discriminate between objects that have only subtle shape differences. Objects with more complex shapes are often described by more than one generalized cone. Objects can be described as hierarchical organized structural models, meaning that their parts are related to each other by spatial relations at multiple scales. That is, a given representation can be refined to the shape and the details of configuration necessary to distinguish it from other objects of similar shape. For example, two different faces might have subtly different relations between the angles of their noses and eyes and subtly different generalized cones representing the shapes of the noses.

One of the most challenging issues in object recognition is the fact that, when rotated in depth, three-dimensional objects change their two-dimensional retinal projection. This problem, called viewpoint invariance, must be addressed by theories of object recognition. Marr and Nishihara (1978) proposed that object parts, encoded as generalized cones, are represented in an object-centered manner, i.e., in a coordinate system that decouples the orientation of the object from the position of the viewer. The significance of this assumption is that the same generalized cone can be recovered from the image regardless the orientation of the object generating that image. Consequently, object recognition performance should be independent of both observer position and object orientation. However, this proposal is based on the era of the computer vision models, and Marr and Nishihara (1978) offered no empirical support for their theory.

By far, the most well-known model of object recognition is the recognition-by-components (RBC) proposed by Biederman (1987). In this model, objects are described as spatial arrangements of a restricted set of roughly 30 basic component shapes, such has 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. Like Marr and Nishihara (1978), 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. Experimental support, both for the importance of the geons in object recognition (Biederman, 1987; Biederman & Cooper, 1991; Biederman & Gerhardstein, 1993; Hummel & Biederman, 1992; Vogels, Biederman, Bar, & Lorincz, 2001) and the idea that object recognition is viewpoint-invariant (Biederman & Cooper, 1992), has been published.

A final issue raised by Biederman (1987) in the RBC model is that object recognition typically occurs at a basic level (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). More specifically, the first and fastest label that is applied to most objects is their category label (e.g., dog). The exception to this rule is visually idiosyncratic category exemplars (e.g., penguin). RBC only explains how observers recognize objects at the category level, making no attempt to account for how we arrive at either superordinate (e.g., animal) or subordinate (e.g., poodle) labels. Thus, there is no particular theory that can explain how such a wide variety of visual recognition tasks are accomplished.

The Contribution of Cognitive Neuropsychology

Individuals with cerebral damage have been the basis of some of the strongest and earliest research of the processing stages that are involved in object recognition. Much of this work comes from case studies of patients who, after suffering cerebral lesions, showed impairments in their ability to recognize stimuli presented in the visual modality (i.e., visual agnosia). The study of such patients led Humphreys and colleagues (Humphreys, Price, & Riddoch, 1999; Humphreys, Riddoch, & Quinlan, 1988; Riddoch & Humphreys, 1987b) to propose a hierarchical model of object recognition. According to this model, object recognition involves a set of separate processes arranged in a hierarchical fashion. This quasi-modular decomposition of object recognition is presented in **Figure 1.1**.

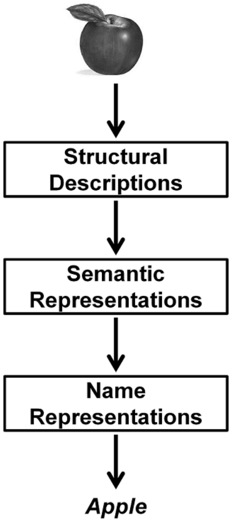

Figure 1.1. A schematic framework illustrating the stages of processing involved in object naming. Adapted from Humphreys, Price and Riddoch (Humphreys, Price, & Riddoch, 1999).

When we see an object, early visual processes encode the shape information and, possibly, other surface details present in the object image. To recognize an object, the encoded perceptual information must be matched against different forms of stored information: knowledge about the form of the object (i.e., its structural description), knowledge about functional and associative properties of the object (i.e., its semantic description), and finally knowledge about the object name (i.e., its phonological description). Access to these various types of knowledge constitutes distinct stages in the recognition process. The first stage is the access to object’s structural description. The encoded perceptual information must be matched against a known form stored in the long-term memory. Evidence for the existence of this separate stage comes from patients who show good early visual processing but have difficulty performing object decision tasks. The performance in these tasks can be assessed with familiarity discrimination tasks between pictures of real objects and non-objects generated by combining parts of different real objects. The same patients are good at retrieving functional and associative properties of the objects via other modalities, indicating that their problem is restricted to visual knowledge about the form of the object (Gainotti & Silveri, 1996; Sartori & Job, 1988). The second stage in object recognition requires access to functional and associative knowledge of the objects. Patients with deficits in retrieving stored semantic representations from the visual modality demonstrate access to stored visual knowledge, as indicated by their ability to perform object decision tasks. However, the same patients may show impairments in matching tasks that require access to semantic knowledge from vision (e.g., match a hammer to a nail or a screw) and object naming (Hillis & Caramazza, 1995; Riddoch & Humphreys, 1987a; Sheridan & Humphreys, 1993). Despite this deficit, these patients demonstrate good performance on tests that require access to semantic knowledge from other modalities (Riddoch & Humphreys, 1987a). Thus, poor object naming cannot be attributed to general deficits in semantic knowledge but, rather, to impaired visual access to semantic knowledge following intact access to stored visual knowledge. These evidences clearly indicate the existence of a separate system that supports long-term visual knowledge about objects, isolated from the functional and associative semantic knowledge system. Finally, the last stage in object recognition is the access to the object's name representation. Evidence for this separate stage comes from patients who are able to make accurate judgments about the visual and semantic properties of objects but cannot readily retrieve phonological information (Kay & Ellis, 1987).

The contribution of cognitive neuropsychology to the study of object recognition was important for the identification of several independent cognitive processes involved in object recognition tasks.

The Neural Basis of Object Recognition

Neuroimaging techniques, specifically functional magnetic resonance imaging (FMRI), offer an opportunity to investigate the neural and cognitive mechanisms underlying object recognition. Objects are represented in a large portion of the visual ventral stream, the processing pathway that extends from the occipital to the inferior temporal lobe. Indeed, FMRI studies have revealed a constellation of object selective brain regions in the lateral and ventral occipito-temporal cortices, referred together as the lateral occipital complex (LOC; Grill-Spector, 2003; Malach et al., 1995; Peissig & Tarr, 2007). The LOC responds more strongly to pictures of objects than to their scrambled counterparts (Grill-Spector et al., 1999; Kourtzi & Kanwisher, 2001; Malach et al., 1995) and shows a number of response properties that characterize an effective object recognition system that subserves perceptual object constancy. First, the LOC responds similarly to objects defined by luminance, texture, motion and other cues, thus representing objects independently of the precise physical cues that define an object (Grill-Spector, Kushnir, Edelman, Itzchak, & Malach, 1998; Kourtzi & Kanwisher, 2000). Second, the LOC represents objects invariant of changing external viewing conditions, such as viewpoint or transformations of object size (Grill-Spector et al., 1999; James, Humphrey, Gati, Menon, & Goodale, 2002; Sawamura, Georgieva, Vogels, Vanduffel, & Orban, 2005; Vuilleumier, Henson, Driver, & Dolan, 2002). These neuroimaging studies are in agreement with early monkey neurophysiological studies in which visual object recognition was mapped to the responses of single neurons in the inferior temporal cortex. For example, Gross and colleagues (Gross, Bender, & Rocha-Miranda, 1969; Gross & Rocha-Miranda, 1972) reported that neurons in the inferior temporal cortex of macaques responded strongly to complex visual stimuli, such as hands and faces. Interestingly, these higher-level areas of the inferior temporal cortex showed very little response to simple stimuli, suggesting that this and related areas are critical to complex visual processing, such as object recognition.

Ungerleider and Mishkin (1982), based on the pattern of behavior following lesions to dorsal and ventral regions of the monkey cortex, suggested that the visual cortex can be broken down into two pathways. The ventral pathway, including areas of the inferior temporal cortex, is involved in the identification of visual objects. The dorsal pathway, including areas of the posterior parietal cortex, is related to spatial properties of vision. An alternative description of the two pathways exists in terms of vision for perception (ventral stream) and vision for action (dorsal stream; Goodale & Milner, 1992). Although neural representations of object information have been extensively studied in the ventral pathway, little is known about the role of the dorsal pathway in object processing. The functional role of the dorsal pathway in object recognition has been frequently attributed to modulation of attention and action guidance (Grill-Spector et al., 1999; Kourtzi & Kanwisher, 2000). However, in a recent neuroimaging study, Konen and Kastner (2008) challenged this idea. The authors found representations for a variety of different object stimuli in the human parietal posterior cortex when action planning was not involved and when attention was drawn away from the stimuli. These results indicate that basic object information related to shape, size and viewpoint may be represented similarly in two parallel and hierarchically organized neural systems in the ventral and in the dorsal pathways.

1.3 Color Processing in the Human Brain

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, namely during object recognition. Although other mammals possess dichromatic or monochromatic color vision, only primates have trichromatic color vision. What is the ecological advantage of having trichromatic color vision? Primates evolved trichromacy 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). 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. Because fruits and leaves play an important role in the primate diet, trichromacy could have evolved as a specific adaptation for finding food (e.g., Osorio & Vorobyev, 1996; Regan et al., 2001). Alternatively, color vision in primates could have evolved for discriminating the spectral modulations on the skin of conspecifics, probably for the purpose of discriminating emotional states, socio-sexual signals and threat displays (Changizi, Zhang, & Shimojo, 2006). Therefore, social and sexual selection could also have played a role in evolution of primate trichromacy. Given that color plays a prominent role in our subjective experience of the visual world, it makes sense to investigate how color information contributes to object recognition.

Cortical Stages of Color Processing in the Human Visual Brain

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, the color center is just part of a more broadly distributed cortical network responsible for color processing that 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 areas 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 human visual system that ensures that the perceived color on a surface 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 see colors consciously. The psychophysical results suggested that color constancy mechanisms were severely deficient in the patient and that his color vision was merely wavelength-based. The imaging studies showed that, when he viewed and recognized colors, significant increases in activity were restricted to V1 and V2, while no activation of V4 was observed.

Corroborating these initial processing states of color perception is the finding that achromatopsia, a condition in which patients report no experience of color, results from lesions in V4. Achromatopsic patients can discriminate between different wavelengths, but they cannot attribute colors to them (e.g., Beauchamp, Haxby, Rosen, & DeYoe, 2000; Kennard, Lawden, Morland, & Ruddock, 1995; Tranel, 2001; Zeki, 1990). Bouvier and Engel (2006) performed a meta-analysis of 92 case reports of achromatopsia in the literature. Lesion overlap analyses revealed a relatively small region of high overlap in the ventral occipital cortex, close to areas that are important for color perception. However, the behavioral deficits in the achromatopsic patients were often incomplete and were not restricted to color vision. Notably, most of the cases reported have concomitant deficits in spatial vision. This observation led the authors to suggest that some visual areas, outside those commonly damaged in achromatopsia, also participate in the color processing stream. This meta-analysis indicates that color perception arises from a stream of processing that flows through multiple visual areas and that achromatopsia likely results from damage to one critical step in the many stages supporting color perception.

Finally, a third and final stage in color processing involves object colors and is supported by the inferior temporal and probably also by the frontal cortex (Zeki & Marini, 1998). Little is known about the neural mechanisms underlying higher-level aspects of color processing. According to the review of the literature, the cortical brain regions believed to be important for color perception are shown in **Figure 1.2**.

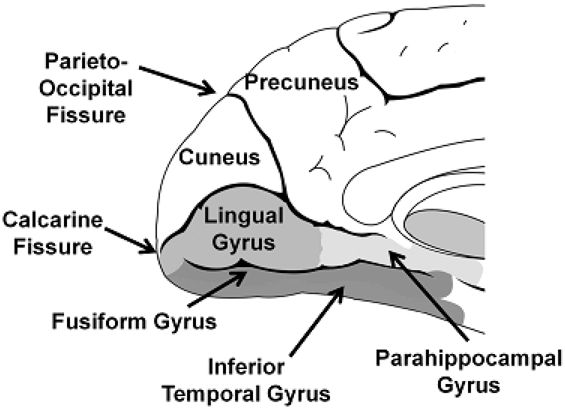

Figure 1.2. Schematic view of the human brain. The regions that are important for various aspects of color perception are shown. These regions include the lingual gyrus and the posterior portion of fusiform gyrus, located below the calcarine fissure.

1.4 Does Color Information Improve Object Recognition?

The role that color plays in object recognition has been a point of contention in the literature. Initially, object recognition theories state that objects are recognized based only on shape information, largely ignoring the influence of color information (Biederman, 1987; Marr & Nishihara, 1978). More recently, a large body of behavioral, neuroimaging and neurophysiological studies indicate 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 1.3**). 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.

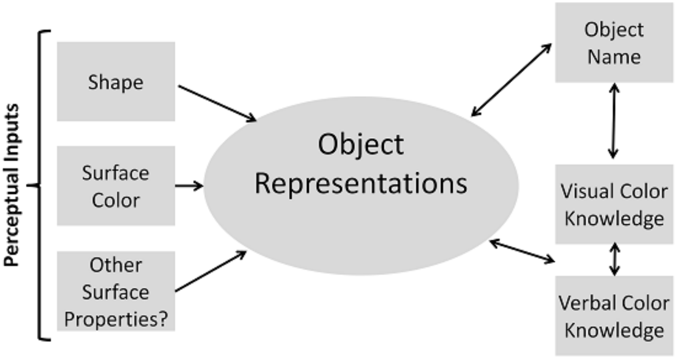

Figure 1.3. The Shape + Surface model of object recognition. Adapted from Tanaka, Weiskopf and Williams (2001).

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; Therriault, Yaxley, & Zwaan, 2009; Wurm, Legge, Isenberg, & Luebker, 1993). 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 strongly associated with a color (i.e., color diagnostic objects; Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999). Although the color red might be useful to recognize strawberries or fire engines, the red color might not be useful to recognize combs or shoes. Additionally, it has been suggested that color might provide important information for people with low visual acuity (Boucart, Despretz, Hladiuk, & Desmettre, 2008; Wurm, Legge, Isenberg, & Luebker, 1993) and patients suffering from visual object agnosia (Humphreys, Goodale, Jakobson, & Servos, 1994; Mapelli & Behrmann, 1997).

Surface Color and Color Knowledge Information

Perceiving that a strawberry is red as opposed to knowing and recalling that a strawberry is red are distinct cognitive operations. The surface color of an object can be defined as the percept generated by the color present in the object image (e.g., the color red in a picture of a red strawberry), while the color knowledge is represented in the semantic information about the prototypical color of an object (e.g., the knowledge that strawberries are typically red).

To study how surface color and color knowledge might interact during object recognition, Joseph and collaborators (Joseph, 1997; Joseph & Proffitt, 1996) manipulated perceptual color input independently of color knowledge in a series of verification tasks. The authors found that color knowledge significantly influenced object recognition. For example, a purple apple was more likely to be mistaken for a cherry than for a blueberry. This interference effect occurs because both apples and cherries are typically red, not because the apple was colored in purple, the typical color of a blueberry. The same pattern of results was obtained when uncolored pictures were used. These findings suggest that the conceptual processing of color does not depend on the presence of a surface color and that automatic color knowledge is more powerful than the perceptual surface color processing during object recognition. However, they allowed participants to verify a target object against three types of different distractors: a distractor similar in shape but not color, a distractor similar in shape and color, and a distractor dissimilar in shape and color. Given that object recognition is a shape-driven system (Tanaka, Weiskopf, & Williams, 2001), a fourth distractor, similar in color and dissimilar in shape, should have been included to exclude the possible interference of shape. Moreover, the effects of color and shape might not be additive; shape and color similarity might yield super additive effects.

At the neuroanatomical level, several studies have tried to clarify whether there are distinct neural regions that process surface color perception and color knowledge retrieval. For example, Martin and colleagues (Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995) used a property production task to activate color and action knowledge associated with objects. Subjects were presented with black and white pictures or the written names of objects and were required to generate words describing an action or a color associated with the presented objects. The type of information that was retrieved modulated activity in the posterior temporal cortex. Relative to action words, color words generation activated the fusiform gyrus anterior to regions associated with color perception and object perception. Activation of the ventral temporal cortex when retrieving color information has been replicated several times using property production (Chao & Martin, 1999; Wiggs, Weisberg, & Martin, 1999) and verification tasks (Goldberg, Perfetti, & Schneider, 2006; Oliver & Thompson-Schill, 2003; Simmons et al., 2007). These results indicate that the ventral temporal cortex is important for color knowledge retrieval. However, it is unclear whether it is also the system that supports color perception. Chao & Martin (1999) addressed this question by evaluating both processes in the same experiment. Color word generation activated the posterior ventral temporal cortex, as previously reported, while passive viewing of colored stimuli activated the lingual gyrus in the occipital cortex. This finding is consistent with studies of color imagery in normal subjects (Howard et al., 1998) and in color-word synesthetes who experience vivid color imagery when hearing words (Paulesu et al., 1995). In both studies, color imagery was associated with activity in the same ventral temporal sites identified in the studies discussed above but not in occipital sites that are active during color perception (e.g., Zeki & Bartels, 1999; Zeki et al., 1991). In addition, neuropsychological studies have reported dissociations between surface color and color knowledge in the ventral occipitotemporal cortex. Although lesions in the posterior fusiform gyrus result in achromatopsia without sacrifice of color knowledge (Bouvier & Engel, 2006), lesions in the ventral temporal cortex result in color agnosia without sacrifice of color perception (Miceli et al., 2001). Coupled with neuropsychological reports of a double dissociation between color perception and color imagery (De Vreese, 1991; Shuren, Brott, Scheft, & Houston, 1996), these data suggest that distinct neural regions appear to be differentially engaged during the processes of color perception and the retrieval of object color knowledge. Information about object color is stored in the ventral temporal cortex. This region is close to, but does not include, the sites in the occipital cortex that selectively respond to the presence of color.

However, the dissociation between perception and knowledge retrieval mechanisms does not necessarily implicate that these two abilities are completely independent. Some neuroimaging studies have claimed that color knowledge modulates regions that are involved in color perception (Goldberg, Perfetti, & Schneider, 2006; Howard et al., 1998; Kellenbach, Brett, & Patterson, 2001; Simmons et al., 2007; Ueno et al., 2007). Some neuroimaging studies have provided additional direct evidence for this claim. Beauchamp and colleagues (Beauchamp, Haxby, Jennings, & DeYoe, 1999) showed that neural activity is limited to the occipital lobes when color perception was tested by passive viewing; however, when the task was made more demanding by requiring subjects to judge subtle differences in hue, activity associated with color perception extended from the occipital cortex into the fusiform gyrus in the ventral temporal cortex. Additionally, Simmons and colleagues (2007), using a task demanding high levels of attention to evaluate color perception and a verbal property verification task to assess color knowledge, found that retrieving information about object color activated the same region of the fusiform gyrus that is activated during color perception (Simmons et al., 2007). Thus, these data support the idea that information about a particular object property, such as its typical color, is stored in the same neural system that is activated when that property is perceived. Therefore, passive color perception may be mediated by occipital cortical regions located early in the visual processing stream, whereas active color perception seems to require more extensive neural activity extending anteriorly into the fusiform gyrus. In a recent review, Martin (2007) suggested that the fusiform gyrus is to provides a neural substrate for acquiring new object-color associations and representing those associations during conceptual processing.

The Color Diagnosticity Hypothesis

The level of color diagnosticity refers to the degree to which a particular object is associated with a specific color. 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. 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). According to this hypothesis, 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, indicating 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 effects of color diagnosticity and its interactions with the observed advantage due to color information in object recognition 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 of 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 certainly not one of the first properties one might think of.

1.5 Specific Aims of the Thesis

The general picture that emerges from the literature is that the role of color information is not well understood. Theories of object recognition have traditionally ignored the role of color information in higher-level vision (Biederman, 1987; Biederman & Ju, 1988). More recently, data from behavioral studies, neuroimaging, and neuropsychological studies have suggested that surface color features and color knowledge information might also contribute to object recognition. However, the conditions under which color information improves object recognition are not well understood. This thesis contributes to this discussion by clarifying some open questions found in the literature. One of the main questions addressed here is the interaction between surface color and color knowledge information during object recognition. It was previously suggested that that object recognition is jointly determined by the bottom-up influence of surface color and the top-down influence of color knowledge information (Tanaka, Weiskopf, & Williams, 2001). However, the way that these two sources of color information interact and which plays the most important role during object recognition is unclear.

Moreover, the color effects on object recognition might depend on the color diagnosticity status of the specific objects. The color diagnosticity status of the objects is probably the most investigated object property in studies that examine the role of color information in object recognition. Color diagnostic objects have a strong association with a particular color; on the other hand, non-color diagnostic objects do not have any specific color association (Tanaka & Presnell, 1999). 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.

The discussion about which type of objects might benefit from color information does not end with the object’s color diagnosticity status. Another object property which effects have been investigated is the object’s semantic category. If color vision developed in humans species to find ripe fruit amongst foliage (Gegenfurtner, 2003; Surridge, Osorio, & Mundy, 2003), it would make sense that recognition of biological objects would benefit more from color information than artifacts. In fact, some studies support this hypothesis (Humphreys, Goodale, Jakobson, & Servos, 1994; Price & Humphreys, 1989). However, more recent data suggest that color information affects object recognition independently of the semantic category (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006).

In this thesis, we present six studies that attempt to clarify these open questions in the literature. In chapters 2 and 3, we try to clarify which type of color information is the most important during object recognition. This question was previously investigated by Joseph and collaborators (Joseph, 1997; Joseph & Proffitt, 1996). In a series of verification tasks, the authors found that color knowledge is more influential than surface color during object recognition (Joseph, 1997; Joseph & Proffitt, 1996). However, during verification tasks, the role of color information was not controlled independently of the role of shape information. Thus, in chapter 2, we try to replicate these findings while independently controlling color and shape information. Participants performed a computerized name-object verification task where the relationship between the color and shape information provided by the object name and by the object picture was manipulated in four conditions: different shape/different color, different shape/same color, same shape/different color, and same shape/same color. If the contribution of color knowledge during recognition is independent of the presence of the appropriate surface color, interference during the non-matching trails should be higher whenever the color knowledge activated by the name and by object picture is the same, not only when pictures are presented in the typical color version, but also in black-and-white and atypical color versions. In chapter 3, we use event-related potentials (ERPs) to further explore this question. Participants performed two color-object verification tasks: a surface color verification task, where they were asked to verify the color of the objects depicted in the image; and a color knowledge verification task, where they were asked to verify the color of the objects in the real world. The surface color of the objects was manipulated to cause interference of the color knowledge information during the surface color task and to cause surface color interference during the color knowledge task. By comparing the ERPs elicited by typical and atypical color presentations in both tasks, we were able to identify at which point during the recognition process subjects recruit surface color and color knowledge information to recognize the presented objects.

In chapter 4 and 5, we examine the interaction between the color diagnosticity status of objects and the manner in which color affects recognition. In chapter 4, participants performed three object recognition tasks with different cognitive demands at the perceptual, semantic and phonological levels. Color and black-and-white versions of color and non-color diagnostic objects were used. By comparing the performance in the three recognition tasks, we identified the visual processing stage at which color information is recruited to recognize color and non-color diagnostic objects. In chapter 5, we used ERPs to further explore this question. In contrast to behavioral measures, the ERPs permits the analysis of cognitive processes with a temporal resolution in a range of milliseconds and represents an optimal approach to study the level at which visual processing of color information improves object recognition. In a recognition task, subjects were presented with color and black-and-white versions of color and non-color diagnostic objects. Color effects were investigated in an early visual ERP component, N1, and in two visual ERP components modulated by higher visual processes, N350 and N400. The study of color information in object and scene recognition has been previously examined using the ERP technique; however, these studies used only high color diagnostic objects or scenes (Goffaux et al., 2005; Lu et al., 2010). For example, Goffaux and colleagues (2005) reported that a color effect can be visualized after 150 milliseconds of the stimuli onset, showing an early role of color information in visual scene recognition (Goffaux et al., 2005).

In chapter 6, we explore whether color information plays different roles when we recognize biological and artifacts objects. More specifically, we investigated whether the neural correlates of color information are the same for biological, artifacts and nonsense objects. Functional magnetic resonance imaging (FMRI) responses were collected during a covert naming task where natural, artifacts and nonsense objects were presented in color and in black and white. The literature suggests that color information is more important for the recognition of objects belonging to natural categories than for the recognition of artifacts (e.g., Price & Humphreys, 1989). Accordingly, different brain regions are expected to be activated during the recognition of colored natural objects and artifacts.

Finally, in chapter 7, we present a review and a meta-analysis that aim to comprehensively integrate and discuss the behavioral literature on the effect of color information during object recognition. We drew some conclusions regarding the moderator role of several variables (e.g., color diagnosticity status and the semantic category of the objects) that are typically manipulated in studies that examine the influence of color information on object recognition.

Chapter 2

The influence of surface color information and color knowledge information in object recognition

Based on:

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Abstract

In order to clarify whether the influence of color knowledge information in object recognition depends on the presence of the appropriate surface color, we designed a name-object verification task. The relationship between color and shape information provided by the name and by the object photo was manipulated in order to assess color interference independently of shape interference. We tested three different versions for each object: typically colored, black and white, and atypically colored. The response times on the non-matching trials were used to measure the interference between the name and the photo. We predicted that the more similar the name and the photo are, the longer it would take to respond. Overall, the color similarity effect disappeared in the black-and-white and atypical color conditions, suggesting that the influence of color knowledge on object recognition depends on the presence of the appropriate surface color information.

2.1 Introduction

The role of surface color in object recognition (i.e., the color present in the image of an object) is an unresolved issue in cognitive science. For example, theories differ on the role shape plays in object recognition (Biederman, 1987; Marr & Nishihara, 1978) and whether other object features, such as surface details, texture, and color, contribute to object recognition (Tanaka, Weiskopf, & Williams, 2001; Tarr, Williams, Hayward, & Gauthier, 1998). Different studies have suggested different roles for color in object recognition. For example, color serves as a perceptual input to early stages of visual processing (Davidoff, Walsh, & Wagemans, 1997; Wurm, Legge, Isenberg, & Luebker, 1993) and is part of the structural representation system of the objects (Price & Humphreys, 1989) or of the semantic system (Davidoff, Walsh, & Wagemans, 1997; Tanaka, Weiskopf, & Williams, 2001). Moreover, color serves as an important cue in object retrieval processes (Lloyd-Jones, 2005; Lloyd-Jones & Nakabayashi, 2009; Vernon & Lloyd-Jones, 2003).

Although it is not yet clear at which level surface color facilitates object recognition, there is a consensus that colored objects and visual scenes are recognized faster than corresponding black and white versions (e.g., Oliva & Schyns, 2000; Rossion & Pourtois, 2004). In order for surface color to be a useful cue for recognition, the participants must decide whether a color is appropriate for a particular object, and it seems plausible that semantic object information (including stored color knowledge) has to be accessed for this to occur. This suggests that prior color knowledge plays a role in object recognition in addition to surface color input, because the color input must in some sense be checked against the activated prototypical color of the object.

In order to study how surface color input and prior color knowledge interact, Joseph and Proffitt (Joseph, 1997; Joseph & Proffitt, 1996) manipulated color knowledge and surface color input independently in a series of verification tasks. The authors found that prior color knowledge was more influential than perceptual input color; for example, a purple apple was more likely to be mistaken for a cherry (typically red) than for a blueberry (typically purple). It was argued that the interference effect is explained by the fact that apples and cherries are prototypically red and not because the apple was colored in purple, the typical color of blueberries. The same pattern of results was obtained when uncolored pictures were used, suggesting that the semantic processing of color is independent of the presence of a perceptual input color.

However, the authors did not fully control whether the interference was caused by prior shape knowledge. In their verification tasks the participants were asked to verify a target object against three different types of distractors: a distractor similar in shape but not similar in color, a distractor similar in shape and color, and a distractor that was dissimilar in both shape and color. To rule out a possible shape interference effect, it is important to include a fourth distractor type that is similar in color and dissimilar in shape. Because shape information is needed for object identity, strong similarity in shape will influence the verification decision. Thus it is important to investigate the previous findings (Joseph, 1997; Joseph & Proffitt, 1996) by controlling color knowledge interference fully independent of shape knowledge interference.

In this study we investigated whether prior color knowledge information takes place in object recognition independently of the presence of the appropriate surface color, controlling the shape information. We designed a verification task in which an object name was presented before an object picture. Two types of trials were included: matching (the name matches the picture) and non-matching (the name does not match the picture). On non-matching trials, the name might activate shape and color knowledge that interferes with shape and color information provided by the picture. To test whether the role of color knowledge information in object recognition is dependent on the presence of the appropriate surface color, three different versions of each object were tested: typically colored, black and white, and atypically colored. If color knowledge information contributes to the recognition process, independently of the presence of the appropriate surface color, it should be more difficult to say “no” whenever the color knowledge activated by the name and by object picture is the same, not only when pictures are presented in their typical color version but also when black-and-white and atypical color versions are presented. In order to assess color interference independently of shape interference, the relationship between color and shape information provided by the name and by the picture was manipulated to assess four possible mismatches: dissimilar shape and dissimilar color, dissimilar shape and similar color, similar shape and dissimilar color, and similar shape and similar color. The interference in the response was measured by the longer response times (Joseph, 1997; Joseph & Proffitt, 1996).

A second aim of this study was to explore the role of color diagnosticity in object recognition. Color diagnosticity is the degree to which a particular object is associated with a specific color. For example, a strawberry – a color diagnostic object – is clearly associated with the red color, whereas a comb – a non-color diagnostic object – is not strongly associated with any specific color. According to the color diagnosticity hypothesis (Tanaka & Presnell, 1999) surface color information improves the recognition of color but not non-color diagnostic objects (see also Nagai & Yokosawa, 2003). However, Rossion and Pourtois (2004) documented that colored objects, independent of the diagnosticity status, were named faster than their noncolored versions (see also Biederman & Ju, 1988; Uttl, Graf, & Santacruz, 2006; Wurm, Legge, Isenberg, & Luebker, 1993). Although color diagnosticity is an important aspect to control when the influence of color information is being studied in object recognition, its role is not well understood. In an attempt to clarify this question, we used in our verification task both color and non-color diagnostic objects. If surface color information is engaged during recognition of both color and non-color diagnostic objects, then the name-picture matching should be faster with typical colored than with black-and-white and atypical color pictures, for both color and non-color diagnostic objects.

2.2 Methods

Participants

Twenty-eight Portuguese graduate students with normal or corrected-to-normal vision volunteered to participate in the experiment (mean age [± *SD*] = 22 ± 4 years, range 18-34 years; mean school years [± *SD*] = 14.5 ± 1 years, range 13-16 years).

Stimuli

The initial pool of pictures consisted of 62 photos of common objects selected from the Reis, Faísca, Ingvar, and Petersson (2006) set. An independent group of 30 participants named and rated the initial set according to prototypicality, familiarity, visual ambiguity, visual complexity, and color diagnosticity. Each photo was presented for 1 min, and participants were asked to write down the name of the object. If they did not know the name, they were asked to mark one of the following categories: *do not know name*, *do not know object*, or *tip-of-the-tongue*. Participants were also asked to evaluate the prototypicality of each photo "according to the degree that the presented picture represents a typical exemplar of the concept" and rated the degree of agreement between the presented photo and their mental image of the concept using a 5-point scale, where 1 indicated low agreement and 5 indicated high agreement. The familiarity of each photo was judged "according to how usual or unusual the object is in your realm of experience", and the participants were asked to rate the concept itself, rather than the photo, using a 5-point rating scale (1 = very unfamiliar, 5 = very familiar). The visual ambiguity of each photo was evaluated "according to how large is the group of different objects that are visually similar with the presented object" (5-point rating scale: 1 = completely nonambiguous object, 5 = completely ambiguous object). Visual complexity was defined as "the amount of detail or intricacy of line in the photo", and the participants were told to rate the photo itself rather than the real-life object (5-point scale: 1 = very low visual complexity, 5 = very complex picture). Color diagnosticity was defined as "the degree to which the object is associated with a specific color" and was also rated on a 5-point scale (1 = low diagnostic color, 5 = high diagnostic color). These instructions are similar to the ones typically used in rating studies (Rossion & Pourtois, 2004; Snodgrass & Vanderwart, 1980; Ventura, 2003).

Following the analysis of the rating scores, we selected only the photos that showed at least 80% name agreement between participants. From these, we selected 16 photos to be used in the experiment: 8 representatives of color diagnostic objects (apple, tomato, carrot, orange, pineapple, pear, onion, and lemon) and 8 representative of non-color diagnostic objects (book, glasses, bowl, pencil, water, can, ruler, and comb). The only significant mean difference between the two groups of objects was color diagnosticity. The mean comparisons between diagnostic and nondiagnostic items on the other rating variables were nonsignificant ($p > 0.5$; **Table 2.1**).

Each colored photograph was used to create a black and white version (using Adobe Photoshop 7.0 "grayscale mode" command, which preserves luminance while discarding color) and an atypically colored version[1] (using Adobe Photoshop 7.0 "variations" command, until a complete transformation of object color was obtained, which preserves luminance). Stimuli luminance was measured using Adobe Photoshop 7.0. We did not find any statistical difference between the diagnostic and nondiagnostic items for the three color versions concerning the luminance values (overall, Mann-Whitney U test: $|Z| = 0.7$, $p > 0.30$).

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[1] For the non-color diagnostic objects we did not construct an atypical color version but just another color version of the same object, because these objects do not have an atypical color associated with them. When we refer to an atypical color version of the non-color diagnostic objects we just mean a second color version of the same object.

Table 2.1. Mean (*SD*) ratings of color diagnosticity, prototypicality, familiarity, visual ambiguity, and visual complexity for color diagnostic and non-color diagnostic objects

	Color Diagnostic Objects	**Non-Color Diagnostic Objects**	**Mann-Whitney U Test**
Color Diagnosticity	4.4 (0.4)	2.3 (0.6)	Z = 3.4, $p < 0.001$
Prototypicality	4.6 (0.2)	4.5 (0.2)	Z = 0.6, $p = 0.5$
Familiarity	4.7 (0.1)	4.6 (0.3)	Z = 0.3, $p = 0.8$
Visual ambiguity	1.9 (0.2)	1.8 (0.3)	Z = 0.4, $p = 0.7$
Visual complexity	2.3 (0.5)	2.4 (0.6)	Z = -0.4, $p = 0.7$

Procedures

A computerized verification task was designed in which an object picture was preceded by an object name. Participants had to decide whether the name and the picture matched. The verification task consisted of 768 trials; half of the trials were matching (384 trials in which the name and the picture matched) and half were non-matching (384 trials in which the name and the picture did not match). On matching trials, the same object was presented eight times in each version (16 objects × 3 versions × 8 times each). On the non-matching trials, 192 trials involved only color diagnostic objects in order to test the interference of shape and color (8 color diagnostic objects × 3 versions × 8 times each); in the remaining 192 trials, diagnostic and non-color diagnostic objects were used as fillers (16 objects × 3 versions × 4 times each). The 192 non-matching trials with diagnostic objects were designed to assess the four possible mismatches between color and shape knowledge activated by the name and the picture (shape/color: dissimilar/dissimilar, similar/dissimilar, dissimilar/similar, and similar/similar; see **Figure 2.1**).

In order to confirm that the four possible mismatches actually activated the same/different color and shape information, 30 independent participants rated the four pairs according to shape and color similarity. The names of the four pairs of stimuli were presented together with four filler pairs, and participants were asked to rate the shape and color similarity between the two concepts. Shape similarity was judged “according to how similar are the two objects in terms of their global shape” (5-point scale: 1 = *the two objects have two completely different shapes,* 5 = *the two objects share the same global shape*). Color similarity was evaluated “according to how similar are the colors of the two objects” (5-point scale: 1 = *the color of the two objects is completely different,* 5 = *the two objects share the same color*). We confirmed that the pairs “tomato-apple” and “onion-lemon” are more similar in term of their global shape (4.1 ± 0.6), compared with the pairs “carrot-orange” and “pineapple-pear” (1.2 ± 0.5; $F(1, 29) = 818.6$, $p < 0.001$). We also confirmed that the pairs “tomato-apple” and “carrot-orange”, (4.2 ± 1.0) are more similar in terms of their color than the pairs “onion-lemon” and “pineapple-pear” (1.6 ± 0.6; $F(1, 29) = 447.8$, $p < 0.001$).

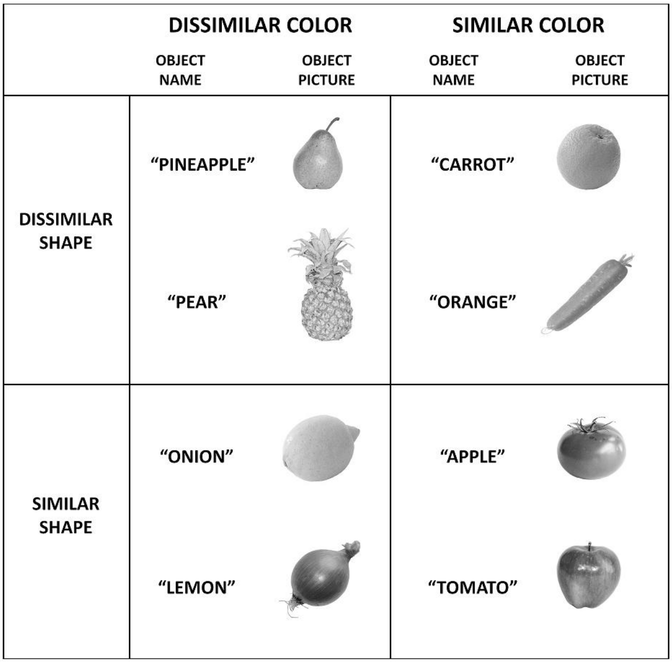

Figure 2.1. Stimuli used in the four possible mismatches between the name and the photo for non-matching trials.

The Presentation 0.7 software (http://nbs.neuro-bs.com/presentation) was used to display the stimuli on a computer screen (size, 17″; spatial resolution, 1024 × 768; color resolution, 24 bits) and to register response times. Each trial started with a fixation cross presented at the center of the screen for 1000 ms. After the fixation cross, the object name (font Arial, font size 70) was presented for 1000 ms, followed by a 500-ms blank screen and then the presentation of the object picture (760 × 550 pixels) for 120 ms. The trial ended with the participant's response. After 1000 ms a new trial started. Participants were instructed to decide as accurately and as quickly as possibly whether the name and the picture matched by pressing one of the two response keys of the keyboard (half of the participants used the right/left hand for "yes"/"no" and the other half for "no"/"yes"). The 768 trials were split into four blocks of 192 trials each. Both blocks and trials within blocks were randomized, and participants were allowed to pause between blocks. Before the experiment, each participant completed a training session with 20 trials.

2.3 Results

The results of the non-matching and matching trials were analyzed by subject (*F*1) and by stimulus (*F*2). A minimum *F* (min*F*) was calculated from the *F*1 and *F*2 analyses. We report *F*1, *F*2, and min*F* values; however, our conclusions are based solely on the conservative min*F* analysis. This approach was taken to ensure the generalizability of results over both subject and stimulus domains (Clark, 1973; Raaijmakers, 2003; see also Raaijmakers, Schrijnemakers, & Gremmen, 1999). None of the main effects or interactions that fail to reach significance in the min*F* procedure are reported.

Non-matching Trials

The non-matching trials included two different types of trials: 192 trials with diagnostic objects that were created to test the interference of shape and color on object verification and 192 trials that served as fillers. Because the experimental question was related exclusively to the diagnostic objects trials, only these verification times were analyzed further. Overall, the participants were able to correctly verify almost all stimuli, and we focused our analysis on the verification times from the correct trials with latencies within 2.5 standard deviations of the mean for each participant and condition. We excluded verification times of incorrect responses as well as long and short verification times (in total 7.5%: 0.9% long, 0.05% short, 6.5% incorrect) from the analysis. The mean of correct response times and the percentage of correct responses for each condition are given in **Table 2.2**.

Verification times were analyzed with a repeated-measures ANOVA including presentation version (typical, black and white, atypical color) as a within-subject or stimulus factor, and shape similarity (similar shape, dissimilar shape) and color similarity (similar color, dissimilar color) were considered within-subject factors in the subject analysis and between-stimuli factors in the item analysis. The results showed a significant presentation version effect ($F1(2, 54) = 9.7$, $p < 0.001$; $F2(2, 8) = 6.6$, $p = 0.02$; $\min F(2, 21) = 3.4$, $p = 0.035$). A post hoc comparison (Tukey's HSD) for the subject analysis showed that the interference was greater on verification times with typical presentations compared with black and white presentations ($p < 0.001$) and with atypical presentations ($p = 0.02$); a main effect of shape similarity was observed ($F1(1, 27) = 44.3$, $p < 0.001$; $F2(1, 4) = 85.7$, $p < 0.001$; $\min F(1, 22) = 29.2$, $p < 0.001$). When shape information between the object name and the object depicted in the photo was similar, there was greater interference compared with the dissimilar case; a main effect of color similarity was also observed ($F1(1, 27) = 28.6$, $p < 0.001$; $F2(1, 4) = 21.4$, $p < 0.001$; $\min F(1, 11) = 12.2$, $p = 0.005$). When the color information between the object name and the object picture was similar, there was greater interference than in the dissimilar case. The two-way interaction between presentation version and color similarity was significant, ($F1(2, 54) = 10.1$, $p < 0.001$; $F2(2, 8) = 10.6$, $p = 0.006$; $\min F(2, 29) = 5.2$, $p = 0.012$, see **Figure 2.2**). A Tukey HSD post hoc comparison for the subject analysis showed that when the color activated by the name and by the object picture was dissimilar, the verification time was equivalent for the three presentation versions (*p* > 0.90). In contrast, when the name and the picture activated the same color, the interference was larger with typical than with black-and-white and atypical color presentations, (*p* < 0.001).

Table 2.2 Mean response time (*SD*) and percentage of correct responses (*SD*) for each non-matching condition

		Presentation Mode					
		Typical color		Black and White		Atypical color	
		RT (*SD*)	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**
Color	**Shape**						
SC	**SS**	641 (119)	89 (10)	602 (114)	89 (13)	625 (125)	91 (8)
SC	**DS**	621 (133)	93 (8)	578 (132)	97 (4)	562 (124)	97 (4)
DC	**SS**	595 (144)	95 (6)	606 (119)	96 (7)	613 (107)	92 (10)
DC	**DS**	576 (111)	95 (7)	559 (114)	97 (5)	573 (129)	90 (8)

Note. DC = dissimilar color between word and image, DS = dissimilar shape between word and image, SC = similar color information between word and image, SS = similar shape between word and image.

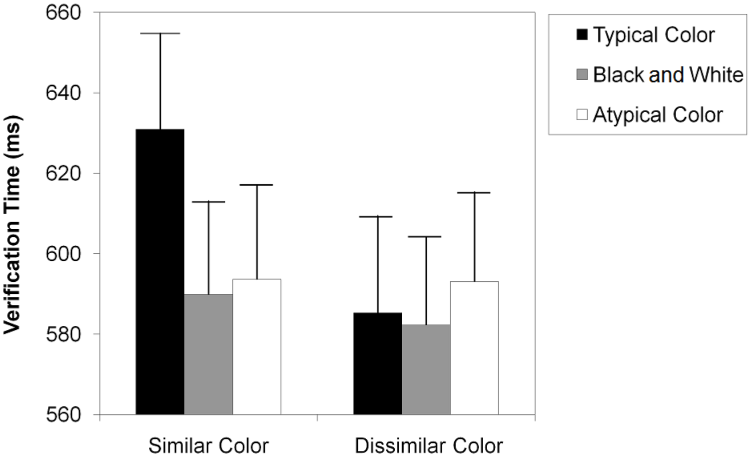

Figure 2.2. Two-way interaction between presentation version and color similarity on non-matching verification times. Bars represent standard error.

Matching trials

As in the case of the non-matching trials, the participants made very few errors on the matching trials (less than 5%). The participants were able to correctly verify almost all stimuli, and we focused our analysis on the verification times from the correct trials with latencies within 2.5 standard deviations of the mean for each participant and condition. We excluded response times from incorrect trials as well as any long or short verification times (in total 5.8%: 0.8% long, 0.2% short, 4.8% incorrect) from the analysis. The mean of correct response times and the percentage of correct responses for each condition are given in **Table 2.3**.

The verification times were analyzed with a repeated-measures ANOVA considering the presentation type (typical, black and white, atypical color) as a within-subject or stimulus factor and diagnosticity (diagnostic, non-color diagnostic objects) as a within-subject factor to the subject analysis and between-stimuli factor to the item analysis, with the correct verification times for matching trials as the dependent variable. The results showed a significant presentation version effect ($F1(2, 54) = 21.2$, $p < 0.001$; $F2(2, 28) = 9.6$, $p < 0.001$; $\mathrm{min}F(2, 53) = 6.6$, $p = 0.003$). A post hoc comparison (Tukey HSD) for subject analysis showed that participants were faster verifying objects presented in typical compared with black-and-white and atypical color ($p < 0.001$); there was also a significant effect of diagnosticity ($F1(1, 27) = 165.6$, $p < 0.001$; $F2(1, 14) = 74.5$, $p < 0.001$; $\mathrm{min}F(1, 27) = 51.4$, $p < 0.001$). Participants were faster verifying nondiagnostic compared with color diagnostic objects. Note that the interaction between presentation version and diagnosticity was not observed (**Figure 2.3**).

Table 2.3. Mean response time (*SD*) and percentage of correct responses (*SD*) for each matching condition

	Presentation Mode					
	Typical color		**Black and White**		**Atypical color**	
	RT (*SD*)	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**
Color diagnostic objects	522 (91)	94 (5)	542 (88)	93 (7)	556 (105)	91 (7)
Non-color diagnostic objects	455 (88)	98 (3)	471 (92)	97 (3)	468 (93)	97 (2)

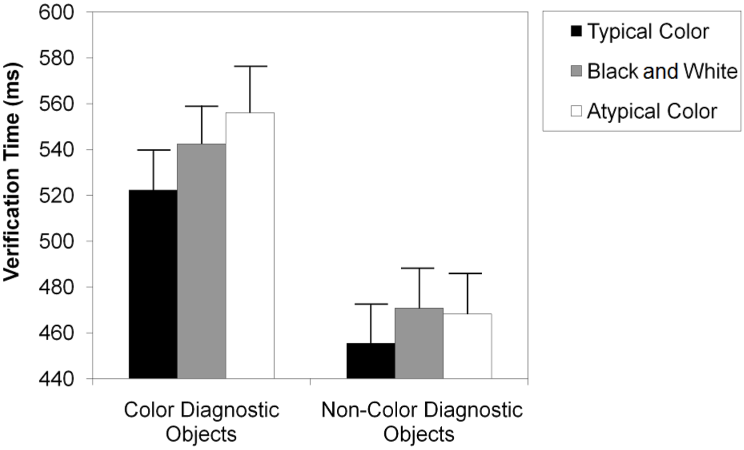

Figure 2.3. Two-way interaction between presentation version and color diagnosticity on matching verification times. Bars represent standard error.

2.4 Discussion

The main aim of this study was to investigate the role of prior color knowledge in object recognition and to test whether and how it interacts with surface color input in object recognition. Participants were presented with an object name, and they had to decide whether the name matched a subsequently presented object picture. The verification times on the non-matching trials were used to measure the interference between the name and the picture. The interference in the response was measured by the longer response times (Joseph, 1997; Joseph & Proffitt, 1996). We predicted that the greater similarity, in terms of shape and color, between the object named and the object pictured, the longer the participants would take to decide whether the name and the picture designated the same or a different object. This was indeed the case. The non-matching verification times were longer when color knowledge activated by the object name was the same as the visual information received from the object picture compared with the conditions in which these two sources provided different color information. This suggests, as expected, that prior color knowledge is recruited during object recognition. In addition, we found a strong interference effect of shape information on the non-matching trials, suggesting that prior shape knowledge is activated in parallel with color knowledge.

The important finding in our study was that the color similarity effect disappeared in the black-and-white and atypical colored conditions, while the interference of shape remained. It thus appears that the activation of color knowledge depends on the presence of the appropriate surface color information: The absence of surface color or wrong surface color neutralizes the observed interference effect. Color knowledge information *per se* does not seem to play an important role in object recognition. The information activated by the word orange interfered with the information activated by the picture carrot only when the carrot was presented in its typical color version and not when the carrot was presented in black and white or in its atypical color version. This finding suggests that it is the appropriate surface color input that promotes the activation of the color knowledge information in the cognitive system. Looking into our data, we could also speculate that color knowledge information is equally important in all conditions as the basis for a rapid heuristic decision, and, consequently, whenever there is not a match between the color information activated by the word and by the image, another criterion must be used to reject the non-matching combination, and this leads to longer response times. If this were the case, the black and white object presentations would also have activated the same color knowledge information as the object word, and then another criterion would be used in order to reject the combination, and consequently the response times should have been also longer. Nevertheless, this was not the case. The explanation that better fits our data is that the appropriated surface color input promotes the color knowledge activation.

Tanaka and collaborators (Tanaka, Weiskopf, & Williams, 2001) proposed the Shape + Surface object recognition model, which suggests that object recognition is jointly determined by the bottom-up influence of the surface color and the top-down influence of the color knowledge. Our results show that the top-down influence of color knowledge is in some way dependent on the bottom-up influence of surface color, suggesting that the color present on the image is responsible for the activation of the stored color information.

Additionally, the results for matching trials showed a robust surface color effect; participants were faster verifying objects presented in their typical color compared with black and white or atypical color. We also found a strong color diagnosticity effect; the verification times were longer for color diagnostic objects compared with non-color diagnostic objects. This finding might be related to the fact that the diagnostic objects in our study were all from natural categories, whereas the non-color diagnostic objects were all from artifact categories. Consistent with this suggestion are the results from studies that investigated category-specific effects in healthy participants. The general pattern of results that emerges from these studies is a recognition advantage for objects from artifact compared with natural categories when the viewing conditions are optimal. Recently Gerlach and collaborators (Gerlach, 2009; Gerlach, Law, & Paulson, 2006; for a different perspective, see Laws & Hunter, 2006) proposed that category-specific effects are driven by the specific processing demands imposed by a given task. Because the shapes of natural objects are more easily configured than the shapes of artifacts, any manipulation that limits how much information may be extracted from the visual impression will make shape configuration harder and would make artifact recognition harder than natural object recognition (e.g., Laws & Neve, 1999; Lloyd-Jones & Luckhurst, 2002). However, if the demand on structural differentiation is high and task conditions are optimal, the shape configuration disadvantage for artifacts may be compensated by more competition for natural objects at the level where visual long-term memory representations compete for selection (e.g., Coppens & Frisinger, 2005; Humphreys, Riddoch, & Quinlan, 1988; Lloyd-Jones & Humphreys, 1997). This is in agreement with our results, where the task viewing conditions were optimal.

Moreover, we found that surface color information helps the recognition of both diagnostic and non-color diagnostic objects. Our results are in concordance with Rossion and Pourtois (2004). The authors did not find a correlation between color diagnosticity and naming latencies, and they argued that color information is an important cue for both diagnostic and nondiagnostic object recognition (see also Biederman & Ju, 1988; Uttl, Graf, & Santacruz, 2006; Wurm, Legge, Isenberg, & Luebker, 1993).

In conclusion, the present study demonstrated that prior color knowledge is engaged during object recognition. However, its role depends on the presence of the surface color input. We suggest that the top-down influence of color knowledge, described in the Shape + Surface (Tanaka, Weiskopf, & Williams, 2001) object recognition model, is driven by the bottom-up influence of appropriate surface color information. Additionally, our results provide evidence that surface color is an important cue to recognize both diagnostic and non-color diagnostic objects.

Acknowledgements

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Chapter 3

The interaction between surface color and color knowledge: Behavioral and electrophysiological evidence

Based on:

Bramão, I., Faísca, L., Forkstam, C., Inácio, F., Araújo, S., Petersson, K. M., & Reis, A. (under revision). The interaction between surface color and color knowledge: Behavioral and electrophysiological evidence. *Brain and Cognition.*

Abstract

In this study, we used event-related potentials (ERPs) to evaluate the relative contribution of surface color and color knowledge information in object identification. We constructed two color-object verification tasks – a surface and a knowledge verification task – using high color diagnostic objects; both typical and atypical color versions of the same object were presented. Continuous electroencephalogram was recorded from 26 subjects. A cluster randomization procedure was used to explore the differences between typical and atypical color objects in each task. In the color knowledge task, we found two significant clusters that were consistent with the N350 and late positive complex (LPC) effects. Atypical color objects elicited more negative ERPs compared to typical color objects. The color effect found in the N350 time window suggests that surface color is an important cue that facilitates the selection of a stored object representation from long-term memory. Moreover, the observed LPC effect suggests that surface color activates associated semantic knowledge about the object, including color knowledge representations. We did not find any significant differences between typical and atypical color objects in surface color verification, which indicates that there is no or little contribution of color knowledge in surface color verification. Our results show that surface color is an important visual cue that triggers color knowledge, and thereby facilitate object identification.

3.1 Introduction

Perceiving that a strawberry is red versus knowing and recalling that a strawberry is red are distinct cognitive operations. The surface color of an object can be defined as the percept generated by the color present in the object image (e.g., the color red in a picture of a red strawberry), whereas the color knowledge is represented in the semantic information about the prototypical color of an object (e.g., the knowledge that strawberries are typically red). Tanaka and collaborators (2001) proposed the Shape + Surface model of object recognition that includes a distinction between surface color and color knowledge. According to this model, object recognition is jointly determined by bottom-up influences (surface color) and top-down influences (color knowledge). In this context, one can ask how these two representations interact during object recognition. It is well documented that surface color contributes to the recognition of diagnostic color objects (for a review, see Tanaka, Weiskopf, & Williams, 2001). For surface color to be a relevant cue in object recognition, cognitive processing must identify whether the color present in the object is or is not appropriate for a given object. For this to occur, semantic color knowledge must be accessed. Following this reasoning, one might hypothesize that when semantic color knowledge is activated together with other visual and functional object properties, recognition is faster and more accurate.

To study how surface color and color knowledge might interact during object recognition, Joseph and collaborators (Joseph, 1997; Joseph & Proffitt, 1996) manipulated the input color independently of color knowledge in a series of verification tasks. The authors found that color knowledge significantly influenced object recognition; for example, an image of a purple apple was more likely to be mistaken for a cherry than for a blueberry. This interference effect occurs because both apples and cherries are typically red and not because the apple was colored purple, the typical color of blueberries. The same pattern of results was obtained when uncolored pictures were used, suggesting that the conceptual processing of color did not depend on the presence of surface color. In their verification tasks participants were asked to verify an object target against three types of distracters: similar in color and shape; dissimilar in color and similar in shape; and a distracter dissimilar in color and shape. In a recent study, we used a similar object verification task where the effect of color information was assessed independently of the effects of shape information, by adding a fourth distracter similar in color and dissimilar in shape in a 2 x 2 factorial design (Bramão, Faísca, Petersson, & Reis, 2010). Since the object recognition system is a shape-driven system (Tanaka, Weiskopf, & Williams, 2001), it is important to experimentally manipulate the effects of color independently of the effects of shape. We observed an interference of color knowledge in object verification when the color knowledge, activated by a previously presented object name (e.g., orange), overlapped with surface color information provided by an object photo (e.g., carrot). This interference effect was strongly dependent on surface color. When the objects were presented in black and white or in an atypical color, the interference effect disappeared. This finding suggests that the appropriate surface color input promotes the activation of stored color knowledge in the cognitive system (Bramão, Faísca, Petersson, & Reis, 2010).

One approach to investigate these processes in the time domain is to characterize the underlying neural processing with event-related potentials (ERPs). Previous ERP studies have identified two different time windows associated with object identification. The first observed difference between successful and non-successful recognition occurs around 250 ms after stimulus onset and is characterized by frontal negativity peaking around 350 ms (N350). The N350 is more negative when the objects are more difficult to recognize or not recognized at all. It has been hypothesized that the N350 reflects the selection of a long-term memory representation – a stored structural description – that best matches the input image (Pietrowsky et al., 1996; Schendan & Kutas, 2002, 2003, 2007). The second observed difference occurs around 550 ms after stimulus onset and is characterized by a broadly distributed late positive complex (LPC). The LPC is also more negative for non-recognized as compared to recognized objects. LPC modulation has been linked to object identification and is hypothesized to reflect the activation of associated semantic knowledge about the object as well as the object name (Mazerolle, D'Arcy, Marchand, & Bolster, 2007; Pietrowsky et al., 1996; Schendan & Kutas, 2002, 2003, 2007; Stuss, Picton, Cerri, Leech, & Stethem, 1992). An additional effect that reflects semantic knowledge integration and/or retrieval is the N400 effect, which was initially related to words that are semantically unrelated or unusual in a given semantic sentence context (Kutas & Hillyard, 1980a, 1980b). The N400 effect is characterized by negativity peaking around 400 ms after stimulus onset (Barrett & Rugg, 1990; Ganis, Kutas, & Sereno, 1996; Hamm, Johnson, & Kirk, 2002; Holcomb & McPherson, 1994; McPherson & Holcomb, 1999; Nigam, Hoffman, & Simons, 1992; Pietrowsky et al., 1996; Pratarelli, 1994; Stuss, Picton, Cerri, Leech, & Stethem, 1992) and was first described for pictures by Barrett and Rugg (1990). The authors reported that pictures that were semantically unrelated to a previous priming stimulus elicit a more negative ERP around 400 ms after stimulus onset, as compared to pictures that were semantically related to a previous primer.

In this study, we recorded ERPs to investigate how surface color and color knowledge interact during object identification. We have previously observed that color knowledge is not automatically activated in the absence of surface color input (Bramão, Faísca, Petersson, & Reis, 2010). Given the fact that stored color knowledge is not necessary to solve the surface color verification task, we predicted that this information would only be activated to a modest degree, if at all. To evaluate this hypothesis, we constructed a color knowledge verification task with high color diagnostic objects, that is, objects that are strongly associated with a prototypical color (Tanaka & Presnell, 1999). Participants were instructed to verify whether the prototypical color of the presented object matched a previously presented color name. The actual object color was manipulated in order to evaluate the contribution of surface color to verification, by presenting objects in both typical and atypical color (see **Figure 3.1**). We predicted ERP differences between typically and atypically colored objects in the ERP components previously identified as being involved in object identification. We assess the role of surface color in the activation of stored color knowledge by comparing atypical versus typical color objects. If the surface color modulates the retrieval of color knowledge, atypical color objects should elicit more negative ERPs in association with the N350 and LPC components. Furthermore, we also explored the differences between matching and non-matching trials. The non-matching condition creates incongruence between the color name and the color knowledge activated by an object. Thus, we expected that non-matching trials were associated with more negative ERPs related to the N400 component, considering the previous findings associating this component with incongruent semantic contexts.

We also evaluate the contribution of color knowledge in the surface color verification task. We have previously observed that color knowledge is not automatically activated in the absence of surface color input (Bramão, Faísca, Petersson, & Reis, 2010). Given the fact that stored color knowledge is not necessary to solve the surface color verification task, we predicted that this information would only be activated to a modest degree, if at all. To investigate this hypothesis, a surface color verification task was designed in which high color diagnostic objects were used. The actual color of the objects was manipulated in order to evaluate the contribution of color knowledge to surface color verification. To that end, we presented both typical and atypical color versions of the same object (see **Figure 3.1**). Participants were instructed to verify whether the surface color of the object matched a previously presented color name. If color knowledge is automatically activated during the surface color verification task, differences in the behavioral and in the electrophysiological results would emerge when comparing atypical and typical color conditions, and when comparing non-matching and matching trails in the ERPs components previously related with object success identification.

3.2 Methods

Participants

Twenty-six right-handed Portuguese native speakers (mean age [± *SD*] = 23 ± 4 years, range 18-32 years; mean years of education [± *SD*] = 14 ± 2 years, range 12-18 years; 9 males and 17 females) with normal or corrected-to-normal vision participated in the study. All subjects completed health questionnaires, and none indicated a history of head injury or other neurological or psychiatric problems. All subjects read and signed an informed consent form describing the procedures, which adhered to the guidelines set out by the Declaration of Helsinki. The study was approved by the local ethics committee.

Stimulus Material

We used eight colors in the experiment (red, gray, orange, green, yellow, brown, pink and white). Each of the colors was easily distinguishable from the others. We selected 56 black and white line-drawings from the picture database at the Max Planck Institute. The drawings in this database are based on the Snodgrass and Vanderwart (1980) set. We selected objects strongly associated with one of selected colors based on the color-diagnosticity scores of Rossion and Pourtois (2004; where, on the original scale, 1 means “the color of the object depicted is not diagnostic at all, i.e., this object could be in any other color equally well” and 5 means “the color depicted is highly diagnostic of the object, i.e., the object appears only with that color in real life”; diagnostic color mean of the selected objects [± *SD*] = 4.4 ± 0.4, range 3.3-5.0). In order to keep color frequency constant, we selected the same number of objects for each color (seven objects strongly associated with each color, in total 8x7 = 56 color-object combinations; **Appendix A**). Adobe Photoshop 7.0 was used to apply the proper color to the internal surface of the objects. To test only color effects, other surface features such as texture and details were removed or minimized.

An atypical color version of each object was created. To construct the atypical color version we rotated the typical colors across objects, whilst ensuring that typical and atypical colored objects were matched for color frequency and luminance. For example, the red color was used to construct the atypical color version of the typical gray objects and the gray color was used to construct the atypical color version of the typical red objects. The three other color pairs used were orange-green, yellow-brown and white-pink.

Experimental Procedures

Two computerized verification tasks were designed: a knowledge verification task and a surface color verification task. In the knowledge verification task, participants were asked to decide whether or not the presented objects were colored with the color of the previously presented color name, in the real world (see **Figure 3.1**). In the surface color verification task, participants had to decide whether or not the presented object was colored with the color of a previously presented color name, ignoring the prototypical color of the object (see **Figure 3.1**). The only difference between the two tasks was the instructions given to the subjects. Each verification task comprised 24 blocks (three blocks for each color). Each block started with the presentation of a color name followed by 28 objects (14 typical color objects – half of them matched and the other half did not match with the given color name – and 14 atypical color objects) and lasted about 2 minutes. In total, each verification task comprised 672 trials, equally divided in two types of trials: matching and non-matching trials. The same object was presented three times in each color version and for each trial type (56 objects x 2 color versions x 3 times each x 2 trial types). Both blocks and trials within blocks were presented in a randomized order. Subjects were encouraged to rest for a few minutes between blocks.

Presentation 0.7 software (http://nbs.neuro-bs.com/presentation) was used to display the stimuli on a computer screen (size: 19’’; spatial resolution: 1024 x 768; color resolution: 24 bits) and to register the response times. Each trial started with a fixation cross (+) presented at the center of the screen for 500 ms, followed by presentation of the object picture (760 x 550 pixels) for 120 ms. Participants were instructed to respond as accurately and as quickly as possibly by pressing one of the two response keys (selection of the response finger was balanced within subjects: half of the participants started with their right/left hand for yes/no responses and in the middle of each verification task the response hand changed). The trial ended with the response of the participant. The inter-stimulus interval (ISI) varied randomly between 750-1250 ms. During this period, indicated by three stars (***) on the screen, subjects were allowed to blink their eyes. The subjects were instructed to fixate on the center of the screen and to avoid eye and body movements during the recording session. The task order was balanced over subjects. Before each verification task and change of response hand, subjects were allowed 16 practice trials.

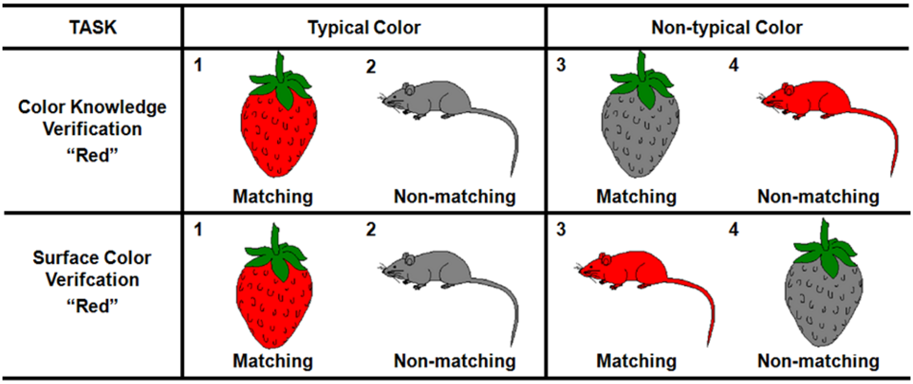

Figure 3.1. Example of the stimuli used in the experiment. The participants had to verify the objects color (surface and knowledge) with a previously presented color name "red". A – Color knowledge verification task, B – Surface color verification task.

EEG Recordings

Continuous electroencephalogram (EEG) was recorded from 64 Ag/AgCl active electrodes held in place on the scalp by an elastic cap. The electrode montage included 10 midline sites and 27 sites over each hemisphere. Two additional electrodes (CMS/DRL nearby Pz) were used as an online reference (for a complete description, see biosemi.com; Schutter, Leitner, Kenemans, & van Honk, 2006). Three other electrodes were attached over the right and left mastoids and below the right eye (to monitor eye movements and blinks). Bioelectrical signals were amplified using an ActiveTwo Biosemi amplifier (DC-67 Hz bandpass, 3dB/octave) and were continuously sampled (24-bit sampling) throughout the experiment at a rate of 512 Hz.

ERP Data Analysis

The EEG data was analyzed using FieldTrip which is an open source toolbox for EEG and MEG analysis developed at the F.C. Donders Centre for Cognitive Neuroimaging (Oostenveld, Fries, & Jensen, 2009; documentation and algorithms available at ru.nl/fcdonders/fieldtrip). ERP data were computed using a 1000 ms epoch (from 200 ms before to 800 ms after the stimulus onset) that was time-locked to the onset of the stimuli. Before averaging, epochs that contained muscle and/or eye movement artifacts were visually rejected, for each subject, and discarded from the analysis. Incorrect response trials were also excluded as well as any trial with implausibly long/short response times. In total, 35.9% of the trials were excluded (7.4% incorrect, 24.2% eye/muscle movement artifacts, and 4.3% excessively long/short response time). The remaining trials were filtered offline, using a low-pass filter of 30 Hz and a high-pass filter of 0.01 Hz and transformed to an average reference (eye electrodes were excluded to compute the common reference). The 200 ms prior to the stimulus onset served as the baseline for the amplitude measurement for each channel. Separate ERP grand-averages were calculated for each experimental condition.

To investigate the contribution of surface color to color knowledge verification as well as the contribution of color knowledge to surface color verification, we explored the differences between the ERPs grand-averages elicited by typical and atypical color objects and by matching and non-matching trials (between 100-800 ms after stimulus onset) in each task using cluster randomization analyses. The cluster randomization method that Fieldtrip uses is an improved version of the method described in Maris (2004; Maris & Oostenveld, 2007). This test effectively controls the Type-1 error rate in a situation involving multiple comparisons (i.e., 64 electrodes X 360 time points). Briefly, the method works as follows: In a first step, all pairs (electrode, time point) are identified for which the t-statistics for the difference between conditions (e.g., atypical *versus* typical color) exceed some prior threshold. In our study, we selected the pairs whose t-statistics exceeded the 5% critical value of the (electrode, time)-specific t-statistics. The selected (electrode, time) pairs are then grouped into a number of clusters in such a way that, within every cluster, the (electrode, time) pairs form a set that is connected spatially and/or temporally. In other words, if the (electrode, time)-specific t-statistics that exceeded the statistical threshold were neighboring either spatially or temporally, these pairs were then grouped together as a cluster. Each cluster is assigned a cluster-level test statistic whose value equals the sum of the (electrode, time)-specific test statistics. Thus, the cluster-level test statistic depends on both the extent of the cluster and the size of the (electrode, time)-specific t-statistics that belong to this cluster. The Type-I error rate for the complete spatiotemporal data matrix is controlled by evaluating the cluster-level test statistic under the randomization null distribution of the maximum cluster-level test statistic. This randomization null distribution is obtained by randomizing the order of the data (e.g., atypical and typical color trials) within every participant. By creating a reference distribution from 4000 random draws, the *p*-value maybe estimated by the proportion from this randomization null distribution in which the maximum cluster-level test statistic exceeds the observed cluster level test statistic (this proportion is called a Monte Carlo *p*-value in the statistics literature). With this number of 4000 random draws, our Monte Carlo *p*-value is an accurate estimate of the true *p*-value. In brief, the cluster randomization *p*-value denotes the chance that such a large summed cluster-level statistic will be observed when there is actually no effect. In this way, significant clusters extending both over time and over electrodes can be identified, providing a measure both of the timing and of the distribution of the effect.

3.3 Results

Behavioral Results

The results of both the non-matching and matching trials were analyzed by subject ($F1$) and by stimulus ($F2$). A minimum F (min$F$) was calculated from the $F1$ and $F2$ analyses. This approach ensured that the results were generalized over both subject and stimulus domains (Clark, 1973; Raaijmakers, 2003; Raaijmakers, Schrijnemakers, & Gremmen, 1999). None of the main effects or interactions that failed to reach significance in the min$F$ calculation are reported.

Overall, the participants were able to correctly verify almost all stimuli and we focused our analysis on the verification times of the correct trials with latencies within 2.5 standard deviations of the mean for each participant and condition. We excluded verification times of incorrect responses as well as implausibly long or short verification times from the analysis. In total, 11.7% of the trials were excluded (7.4% incorrect and 4.3% excessively long/short response time). Verification times were analyzed with a repeated-measures ANOVA including task (surface task, knowledge task), color (typical color, atypical color) and matching (matching trials, non-matching trials) as within-subject/stimulus factors. The results showed a significant task effect ($F1(1, 25) = 202.7$, $p < 0.001$; $F2(1, 55) = 1463.8$, $p < 0.001$; min$F(1, 32) = 178.1$, $p < 0.001$) – subjects responded faster in the surface verification task compared with the knowledge verification task; a main color effect was observed ($F1(1, 25) = 128.5$, $p < 0.001$; $F2(1, 55) = 123.1$, $p < 0.001$; min$F(1, 70) = 62.9$, $p < 0.001$) – subjects responded faster to typical color objects as compared to atypical color objects; and finally also a main significant effect of matching was also observed ($F1(1, 25) = 196.3$, $p < 0.001$; $F2(1, 55) = 386.2$, $p < 0.001$; min$F(1, 51) = 130.1$, $p < 0.001$) – subjects responded fast to matching trials then to non-matching trials. The two-way interaction between task and color was significant ($F1(1, 25) = 94.3$, $p < 0.001$; $F2(1, 55) = 119.7$, $p < 0.001$; $\min F(1, 62) = 52.7$, $p < 0.001$). A Tukey HSD post-hoc comparison for the subject analysis showed that in the knowledge verification task subjects were faster in responding to the typical as compared to the atypical color presentation ($p < 0.001$); however, in the surface task, subjects respond equally fast to typical and atypical color presentations ($p = 0.95$). The two-way interaction between color and matching was also significant ($F1(1, 25) = 27.8$, $p < 0.001$; $F2(1, 55) = 34.4$, $p < 0.001$; $\min F(1, 63) = 15.4$, $p < 0.001$). A Tukey HSD post-hoc comparison for the subject analysis showed that when the trials were matching the difference between typical color and atypical color was bigger ($p < 0.001$) than when the trials were non-matching ($p = 0.005$). The three-way interaction was also significant ($F1(1, 25) = 22.7$, $p < 0.001$; $F2(1, 55) = 21.0$, $p < 0.001$; $\min F(1, 71) = 10.9$ $p = 0.002$; see **Figure 3.2**). A Tukey HSD post-hoc comparison for the subject analysis showed that in the surface verification task subjects performed equally fast the task independently of the color presentation, both in the matching and in the non-matching trails ($p = 0.9$); In the color knowledge verification task, subjects were faster performing color verifications in the typical color version; however the advantage of color presentation was bigger for the matching trials ($p < 0.001$) compared to the non-matching trials ($p = 0.01$).

Electrophysiological Results

Color knowledge verification task

The color effect was explored through the contrast between atypical and typical color objects, in both the matching and non-matching trials. In the matching trials, the color effect was associated with a greater average negative potential over 26 anterior electrodes in a time window of 300-500 ms post-onset of the stimulus, consistent with an N350 effect (sum-$T = -6309.8$; $p < 0.001$), with a corresponding positive effect occurring over 20 posterior channels (sum-$T = 3204.6$; $p = 0.001$; **Figure 3.3-A**).

In the non-matching trials, the N350-like effect was observed in two different clusters, showing that atypical color objects were associated with a frontocentral potential of greater negativity (**Figure 3.3-B**). The first cluster was found in a time window of 260-320 ms after stimulus onset over 22 frontal electrodes (sum-T = -1337.4; $p = 0.005$), with a corresponding positive effect observed in 18 posterior channels (sum-T = 479.3; $p = 0.05$). Additionally, a second significant cluster was found, also consistent with the N350-like effect, over 13 frontal right channels (sum-T = -1021.6; $p = 0.01$) between 380-490 ms after stimulus onset. Finally, around 580-720 ms after stimulus onset, we observed that atypical color objects once more induced higher negativity in one cluster (sum-T = -1570.2; $p = 0.004$) over 10 right frontal channels, consistent with the LPC effect (**Figure 3.3-B**).

To explore the difference between non-matching and matching trials, we compared these two trial types with regard to typical and atypical color objects. The cluster randomization analysis identified that the non-matching trials were associated with greater central negativity compared with the matching trials for both the typical and atypical color objects in a time window of 350-600 ms post-onset of the stimulus, consistent with an N400-like effect. In the typical color objects, the non-matching trials were associated with a greater average negative potential over 29 central electrodes (sum-T = -7804.5; $p < 0.001$), with a corresponding positive effect occurring over 27 periphery channels (sum-T = 3204.6; $p = 0.003$; **Figure 3.4-A**). For the atypical color objects, the central negativity was significant over 19 channels (sum-T = -5893.7; $p < 0.001$), with one corresponding positive effect occurring over 12 peripheral channels (sum-T = 2016.3; $p = 0.006$; **Figure 3.4-B**).

Surface color verification task

In this task, we did not observe any significant difference between atypical and typical color objects in either the matching (**Figure 3.5-A**) or the non-matching trials (**Figure 3.5-B**).

To investigate the matching effect in the surface color verification task, we compared the non-matching trials against the matching ones for both typical and atypical color objects. For the typical color objects, the non-matching trials were associated with greater frontal negativity compared with the matching trials in a time window of 215-280 ms post-onset of the stimulus, over 26 channels (sum-*T* = -2499.8; *p* < 0.001). We observed a corresponding positive effect over 15 posterior channels (sum-*T* = 893.7; *p* = 0.006; **Figure 3.6-A**). A second significant cluster associating the non-matching trials with greater central negativity was found over 18 central channels (sum-*T* = -3004.8; *p* < 0.001), with a corresponding positive effect occurring in 13 peripheral channels (sum-*T* = 603.3; *p* = 0.016; **Figure 3.6-A**), between 315-480 ms after stimulus onset. Similar results were found for the atypical color objects. The cluster analysis also identified two significant clusters showing that the non-matching responses were associated with greater frontal-central negativity, compared with the matching responses. The first cluster was found over 27 frontal channels (sum-*T* = -2243.3; *p* = 0.008; **Figure 3.6-B**) between 210-280 ms post-onset of the stimulus and the second cluster identified 10 central electrodes (sum-*T* = -606.6; *p* = 0.03; **Figure 3.6-B**) between 320-370 ms post-onset of the stimulus.

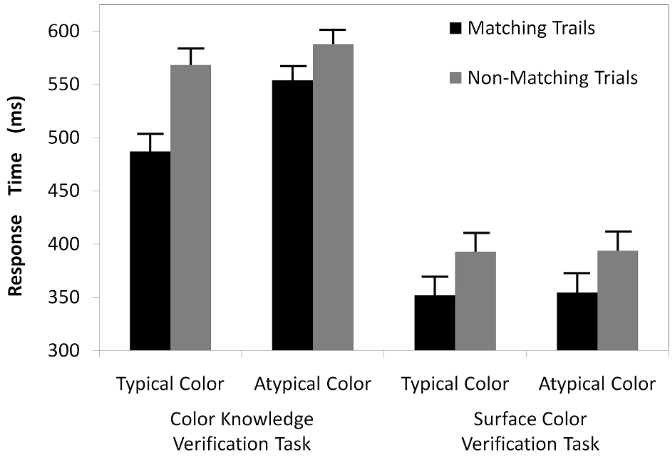

Figure 3.2. Three-way interaction between the factors task, color and matching factors. Error bars represent the standard error.

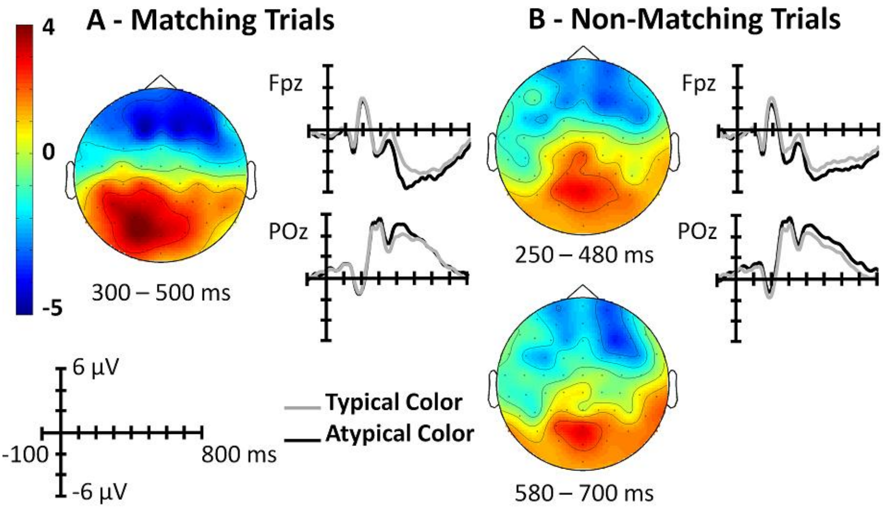

Figure 3.3. Topographic distribution of the atypical *versus* typical color objects in the knowledge color verification task for the matching (A) and non-matching verification (B). Time windows of significant differences are plotted. The ERP traces for the typical and atypical color objects at two representative electrode sites (Fpz and Poz) for the matching (A) and non-matching verification (B) are shown.

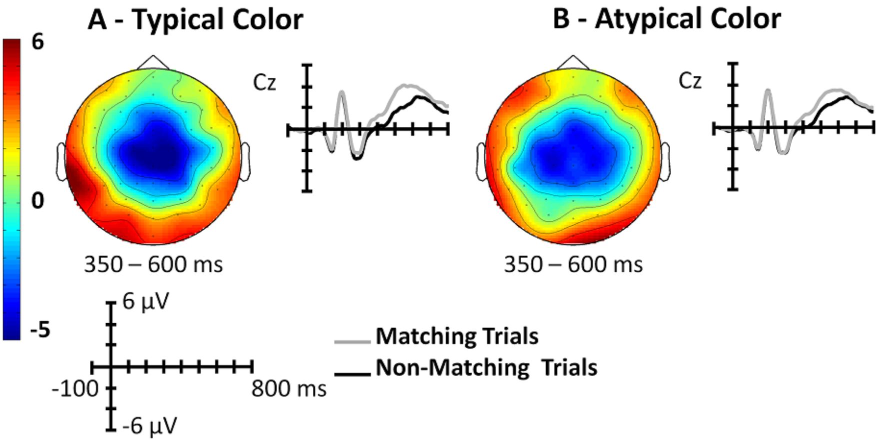

Figure 3.4. Topographic distribution of the non-matching *versus* matching trails in the color knowledge verification task for the typical (A) and atypical color objects (B). Time windows of significant differences are plotted. The ERP traces for the matching and non-matching trial at one representative electrode sites (Cz) for the typical (A) and atypical color objects (B) are shown.

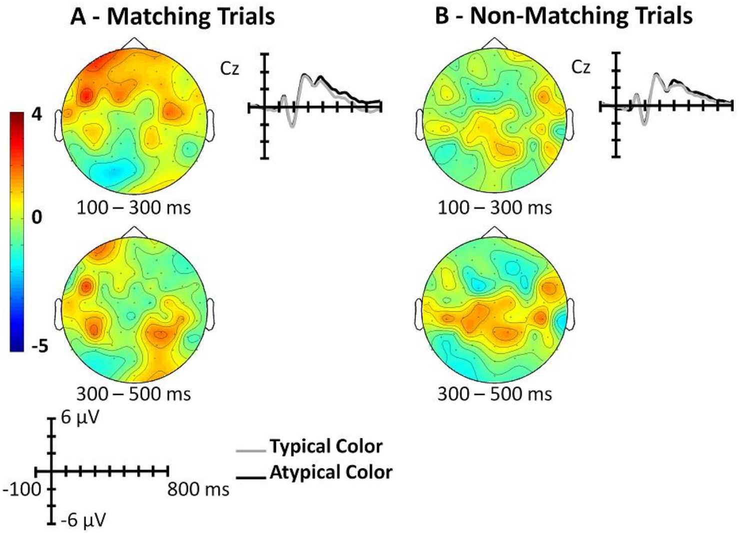

Figure 3.5. Topographic distribution of the atypical *versus* typical color objects in the surface color verification task for the matching (A) and non-matching verification (B). Two different time windows are plotted. The ERP traces for the typical and atypical color objects at one electrode sites (Cz) for the matching (A) and non-matching verification (B) are shown.

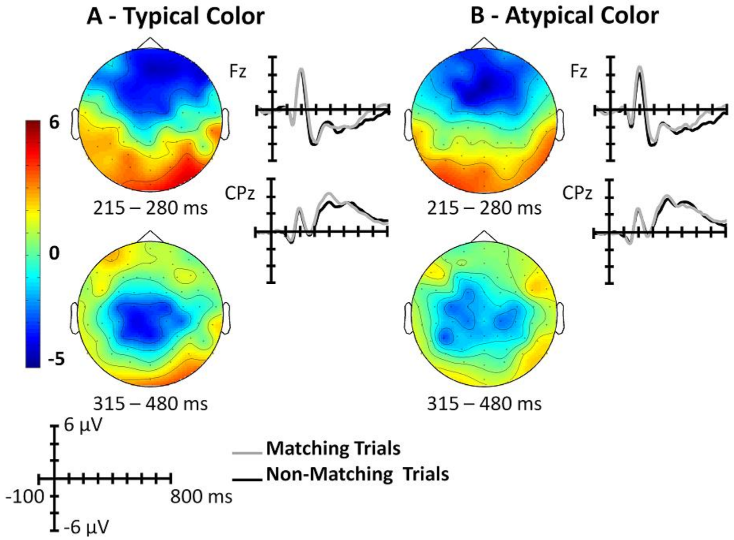

Figure 3.6. Topographic distribution of the non-matching *versus* matching trails in the surface color verification task for the typical (A) and atypical color objects (B). Time windows of significant differences are plotted. The ERP traces for the matching and non-matching trial at two representative electrode sites (Fz and CPz) for the typical (A) and atypical color objects (B) are shown.

3.4 Discussion

In this study, we used event-related potentials (ERP) to better understand the contribution of color perception and stored color knowledge to object identification. We designed two color-object verification tasks – a surface color and a color knowledge verification task – where both typical and atypical color versions of the same high color diagnostic objects were presented. In the color knowledge task, the subjects were asked to verify whether or not the prototypical color of the presented objects matched with a previously presented color name, independently of the actual color of the presented object. The object color was manipulated in order to evaluate the contribution and the interference of surface color information during object identification. On the other hand, in the surface color verification task, subjects were asked to verify whether or not the color of the presented object matched with a previously presented color name, independently of the prototypical color of the object. The actual object color was manipulated in order to evaluate the contribution and the interference of stored color knowledge with regard to the surface color task.

Our results showed that the atypical color objects were associated with significant N350 and LPC effects in the knowledge color task, whereas no differences were found between the atypical and typical color conditions in the surface color task. In color knowledge verification, the differences observed between the ERP elicited by atypical and typical color objects were temporally and topographically consistent with an N350-like effect. Atypical color objects were associated with a more negative ERP over the frontal sites during the time window between 300-500 ms after stimulus onset. The N350 marks the first ERP component associated with identification success; the N350 is smaller for correctly identified compared to unidentified objects, it is sensitive to the recoverability of perceptual structure, and it is an index of the matching process between the perceptual input with a template stored in the long-term memory (McPherson &

Holcomb, 1999; Schendan & Kutas, 2002). The visual knowledge enabling this matching ability is of generic semantic type (Schendan & Kutas, 2002, 2003, 2007). Additional findings suggest that the N350 is larger for more complex images (Ruchkin, Johnson, Canoune, & Ritter, 1991; Schendan & Kutas, 2002; Stuss, Sarazin, Leech, & Picton, 1983) as well as for non-typical image views relative to easier to recognize, canonical views, consistent with the idea that the N350 effect is related to the selection of a stored structural description model to match against the perceptual input (Schendan & Kutas, 2003). Our results are consistent with previous research on the N350 effect and show that color information is activated in the N350 time window. This, together with the fact that subjects were faster in verifying typical color objects, suggests that shape and color effects are combined to facilitate the selection of structural descriptions from the long-term memory in this time window. The fact that we did not observed surface color effects in early ERP components corroborates the account that color information is activated together with the structural description. In this context, the typical surface color might limit the possible structural descriptions that match with the presented object in the early part of the identification process. In addition, for the non-matching trials in the color knowledge verification task, we observed an effect post-500 ms (referred to as LPC), with a typical frontal topography (Hanslmayr et al., 2008; Liotti, Woldorff, Perez, & Mayberg, 2000). This shows that atypical color objects were associated with a more negative ERP over the frontal sites during the time window between 580-720 ms after stimulus onset. Previous ERP studies suggest that the LPC effect is related to activation of associated semantic knowledge (e.g., Mazerolle, D'Arcy, Marchand, & Bolster, 2007). Similarly to the N350 effect, the LPC effect varies with recognition success; however, unlike the N350, the LPC (including posterior N400 and P600) shows categorization modulations for any image, regardless of recoverability, and may index a fronto-parietal network for categorization-related processes, such as selection of an appropriate response, including a name (Schendan & Kutas, 2002, 2003, 2007).

Although LPC repetition effects could reflect memory for these later categorization processes, most evidence suggest that these effects reflect conscious recollection (Duarte, Ranganath, Winward, Hayward, & Knight, 2004; Paller, Kutas, & McIsaac, 1995). The color effects found in this ERP component suggest that typical color facilitates the activation of semantic object knowledge. Taken together, the LPC and N350 effects that we observed suggest that object color helps in the identification process, by facilitating access to the structural description and associated semantic knowledge about the object. The behavioral results are also consistent with this idea. We observed that subjects were faster in responding to the typical color objects in both matching and non-matching trials.

Additionally, the matching effect in the color knowledge verification task showed that non-matching trials were associated with a more negative potential over the central channels in a time window between 350-600 ms after stimulus onset, consistent with an N400-like effect. This significant N400-like effect was found for both typical and atypical color objects, suggesting that semantic knowledge about the object color was activated during the task, even when the objects were presented in a non-typical color (e.g., a strawberry painted in gray). Whenever the color knowledge activated by the object did not match with the previous presented color name (non-matching trial), a greater N400 was observed. This result is consistent with previous literature showing N400 effects when a picture is semantically anomalous in a given context (e.g., Hamm, Johnson, & Kirk, 2002).

In the surface verification task, we did not find any significant effects related to color knowledge (neither behavioral nor ERP effects). A possible explanation is that the cognitive system does not use color knowledge to perform surface color verification. Subjects verified equally fast and use the same cognitive resources to determine that a red strawberry (a typical red object) and a red mouse (a typical non-red object) are colored red, and that a gray strawberry and a gray mouse are not colored in red. Thus, we suggest that when color knowledge is not necessary or needed to perform a task, this information is not automatically recruited. An alternative interpretation is that subjects performed the surface verification before object color knowledge was activated, or possibly that the task was too easy and did not implicate complete object recognition to accurately perform the task. These arguments could justify the absence of effects that could be discerned among the behavioral results; however, they cannot justify the lack of ERP effects. It is well documented that ~200-300 ms after stimuli onset, functional and perceptual properties of the objects are automatically activated (Vihla, Laine, & Salmelina, 2006). Thus, our results suggest that color knowledge may be activated conditionally during surface color verification. Nevertheless, we believe that it is important to replicate this result in a more complex surface color verification task.

Furthermore, we observed that non-matching trials in the surface color verification task were associated with a more negative potential over the frontal sites ~200 ms after stimulus onset and with a more central negative potential ~300 ms after stimuli onset, compared with the matching trials. This negative frontal potential shares some properties with the N2 component, with regard to both latency and topographic distribution (Folstein & Petten, 2008). N2 effects have been shown in conditions that require inhibition of a prepared response and/or contain elements suggesting two conflicting responses, as compared to conditions without response inhibition or response conflict (Nieuwenhuis, Yeung, Wildenberg, & Ridderinkhof, 2003; Pfefferbaum, Ford, Weller, & Kopell, 1985). Folstein and collaborators (Folstein & Petten, 2008; Folstein, Van Petten, & Rose, 2008) suggested that enhancements of N2 due to conflicting information occur when participants begin to prepare a motor response before evaluation of a stimulus is complete. This hypothesis suggests that the N2 effect is sensitive to response conflict (Folstein, Van Petten, & Rose, 2008). In accordance with this idea, we suggest that the N2 effect found in our study is related with motor-related preparation, and whenever an object was colored in a different color from the previously presented color name (non-matching trial), a stronger N2 component was elicited.

Overall, our results suggest that color perception is a process relatively independent of the access to stored knowledge about object color and subjects seem to perform surface color verifications without the automatic activation of object-associated color knowledge. However, we also showed a strong interference of surface color in the color knowledge task. It therefore appears that the appropriate surface color prompts the activation of color knowledge in the cognitive system. Although color knowledge could be activated without the presence of color input, the actual color input triggers color knowledge and thus contributes to more efficient object recognition.

At the neuroanatomical level, distinct neural regions appear to be differentially engaged during the processes of color perception and the retrieval of object color knowledge. Whereas color perception is more closely associated with the occipital and posterior occipitotemporal cortex (Bartels & Zeki, 2000; Chao & Martin, 1999; Zeki & Marini, 1998), color knowledge is associated with the left anterior inferior temporal, left frontal and left superior parietal regions of the brain (Chao & Martin, 1999; Wiggs, Weisberg, & Martin, 1999). Also, neuropsychological studies have reported dissociation between surface color and color knowledge in the ventral occipitotemporal cortex. Whereas lesions in the lingual gyrus result in achromatopsia in the presence of spared color knowledge (Bouvier & Engel, 2006), lesions in the ventral temporal cortex results in color agnosia with spared color perception (Miceli et al., 2001). Together, these studies suggest that the brain regions engaged during the retrieval of object-color knowledge are different from those areas engaged during color perception. However, the dissociation between perception and knowledge retrieval mechanisms does not necessarily imply that these two abilities are completely independent. For example, some neuroimaging results suggest that color knowledge modulates regions that are involved in color perception (Goldberg, Perfetti, & Schneider, 2006; Howard et al., 1998; Kellenbach, Brett, & Patterson, 2001; Simmons et al., 2007; Ueno et al., 2007).

Previous studies have investigated color perception with the ERP technique (Anllo-Vento, Luck, & Hillyard, 1998; Buchner, Weyer, Frackowiak, Romaya, & Zeki, 1994; Edwards, Xiao, Keysers, Földiák, & Perrett, 2003; Goffaux et al., 2005; Lu et al., 2010; Plendl et al., 1993; Proverbio, Burco, Zotto, & Zani, 2004). For instance, Goffaux and colleagues (2005) measured early ERPs to examine the effect of color cues on scene categorization. The ERPs associated with the black and white images and with the atypical colored scenes were delayed compared to the ones associated with the typical colored scenes. The color effects were mirrored in the early (150 ms following stimulus onset) frontal EEG correlates (Goffaux et al., 2005).

The objective of the present study was to provide additional evidence in order to understand how top-down color knowledge and bottom-up color perception interacts during object recognition. Our study provides electrophysiological evidence suggesting an interaction between surface color and color knowledge retrieval.

Acknowledgements

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Chapter 4

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

Based on:

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Abstract

In the present study, the authors explore in detail the level of visual object recognition at which perceptual color information improves the recognition of color diagnostic and non-color diagnostic objects. To address this issue, 3 object recognition tasks, with different cognitive demands, were designed: an object verification task, a category verification task, and a name verification task. They found that perceptual color information improved color diagnostic object recognition mainly in tasks for which access to the semantic knowledge about the object was necessary to perform the task; that is, in category and name verification. In contrast, the authors found that perceptual color information facilitates non-color diagnostic object recognition when access to the object's structural description from long-term memory was necessary – that is, object verification. In summary, the present study shows that the role of perceptual color information in object recognition is dependent on color diagnosticity.

4.1 Introduction

The visual system recognizes objects via multiple features, such as shape, color, texture, motion characteristics, and others. All of these features contribute to object recognition. The roles of these perceptual cues or properties in object recognition have been extensively investigated. For example, several studies have investigated the influence of color information on object recognition. However, some of the findings that have emerged from these studies appear inconsistent. For instance, some early studies failed to identify a role for color information in object recognition (Biederman & Ju, 1988; Davidoff & Ostergaard, 1988), whereas more recent investigations have reported that color input improves visual recognition, both for objects and scenes (e.g., Gegenfurtner & Rieger, 2000; Therriault, Yaxley, & Zwaan, 2009).

Different explanations have been proposed for these results. For instance, it has been suggested that color details improve object recognition in the following situations: when shape information is degraded (Tanaka & Presnell, 1999), when the shape is not diagnostic for the object (Price & Humphreys, 1989), in conditions such as low visual acuity (Wurm, Legge, Isenberg, & Luebker, 1993) and visual object agnosia (Mapelli & Behrmann, 1997), when the objects are from biological categories (Price & Humphreys, 1989), and when objects are strongly associated with a color (color diagnostic objects; Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999). The level of color diagnosticity refers to the degree with which a particular object is associated with a specific color. For example, a strawberry, which is a color diagnostic object, is strongly associated with the color red, whereas a comb, which is a non-color diagnostic object, is not strongly associated with any particular color. According to the color diagnosticity hypothesis (Tanaka & Presnell, 1999), color information improves the recognition of color diagnostic objects but not non-color diagnostic objects (see also Nagai & Yokosawa, 2003). However, the field has not yet reached a consensus concerning these matters. Recent studies have found that perceptual color information improves object recognition independent of the semantic category and color diagnosticity (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). Overall, these findings suggest that the role of perceptual color in object recognition is not well understood.

In this study, our goal was to investigate at which stage of visual processing perceptual color information modulates the recognition of color diagnostic and non-color diagnostic objects. We hypothesized that perceptual information related to input color improves the recognition of color diagnostic and non-color diagnostic objects at different levels of the visual recognition process. Experimental evidence has shown that perceptual color information is an important cue for activating semantic object knowledge, including the object's typical color, and probably other perceptual and functional properties, thus facilitating object recognition (Bramão, Faísca, Petersson, & Reis, 2010). However, this is likely to be the case only for color diagnostic objects, because they are strongly associated with a particular color, in contrast to non-color diagnostic objects. Moreover, there is also experimental evidence that shows that perceptual color has another role in addition to facilitating access to semantic object representations: serving as a perceptual input to the early stages of visual processing (Davidoff, Walsh, & Wagemans, 1997; Gegenfurtner & Rieger, 2000; Wurm, Legge, Isenberg, & Luebker, 1993). Thus, we predict that color information also participates in the early stages of visual processing, in addition to facilitating access to the semantic representation for color diagnostic objects. However, for non-color diagnostic objects, perceptual color is only expected to facilitate the early stages of visual processing.

To investigate this question, we constructed three different object recognition tasks for both color diagnostic and non-color diagnostic objects: 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, 1987b). 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 level of object processing at which color information facilitates the recognition of color diagnostic and non-color diagnostic objects. If color information improves the recognition of color diagnostic objects both at the early visual stages and at the semantic level, 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.

Finally, there is evidence that object recognition is faster for photographs than line-drawings (Brodie, Wallace, & Sharrat, 1991; Price & Humphreys, 1989). Uttl and colleagues (Uttl, Graf, & Santacruz, 2006) have argued that line-drawings typically are viewed as a representation of an object class – a type – whereas photographs are viewed as a particular individual object – a token. To a certain extent, the recognition of types and tokens may recruit different perceptual and semantic processes (Uttl, Graf, & Santacruz, 2006). In this study, we also investigated whether the color effects are the same or different for line-drawings and photographs of the same objects.

4.2 Methods

Participants

One hundred and forty-four Portuguese students with normal or corrected-to-normal vision volunteered to participate in the experiment (mean age [± *SD*] = 23 ± 4.5 years, range 18-40 years; mean years of education [± *SD*] = 15 ± 2 years, range 12-20 years; 99 females and 45 males).

Stimuli

The initial pool of pictures consisted of 220 photos of common objects. Some photographs were selected from the Focus Multimedia CD Photo Library, some were selected from the set of Reis and colleagues (Reis, Faísca, Ingvar, & Petersson, 2006), and some were selected via an Internet image search using the Google search engine. An independent group of 30 participants named and rated the initial set according to prototypicality, familiarity, visual ambiguity, visual complexity, and color diagnosticity. Each photo was presented for 1 min, and the participants were asked to write down the name of the object. If they did not know the name, they were asked to choose one of the following categories: *do not know name*, *do not know object*, or *tip of the tongue*. Participants were also asked to evaluate the prototypicality of each photo “according to the degree that the presented picture represents a typical exemplar of the concept”; they were also asked to rate the degree of agreement between the presented photo and their mental image of the concept using a 5-point scale, where 1 indicated low agreement and 5 indicated high agreement. The familiarity of each photo was judged “according to how usual or unusual the object is in your realm of experience”, and the participants were asked to rate the concept itself, rather than the photo, using a 5-point rating scale (1 = very unfamiliar; 5 = very familiar). The visual ambiguity of each photo was evaluated “according to how large is the group of different objects that are visually similar to he presented object” (5-point rating scale: 1 = completely nonambiguous object; 5 = completely ambiguous object). The visual complexity was defined as “the amount of detail or intricacy of line in the photo”, and the participants were asked to rate the photo itself rather than the real-life object (5-point scale: 1 = very low visual complexity; 5 = very complex picture). The color diagnosticity was defined as “the degree to which the object is associated with a specific color” and was also rated on a 5-point scale (1 = low color diagnostic; 5 = a high color diagnostic). These instructions are similar to those typically used in object picture rating studies (Rossion & Pourtois, 2004; Snodgrass & Vanderwart, 1980; Ventura, 2003).

Following the analysis of the rating scores, we selected only those photos that showed at least 80% name agreement between participants. Of these, we selected 72 photos to be used in the experiment. The objects were divided according to their color diagnosticity into a group of high-color diagnostic objects (20 from natural categories and 16 from artifact categories; **Appendix B**) and a group of low-color diagnostic objects (16 from natural categories and 20 from artifact categories; **Appendix B**). The only significant mean difference between the two groups of objects was color diagnosticity. The mean comparisons between color diagnostic and non-color diagnostic items on the other rating variables were not significant ($p > 0.2$; **Table 4.1**).

Each photograph was matched with a line-drawing that was as similar as possible in terms of shape, size and orientation. The line-drawings were selected from the picture database at the Max Planck Institute. A total of 60 of the 72 selected pictures were similar to the original Snodgrass and Vanderwart (1980) set. We used Adobe Photoshop CS2 to create four versions of each object: a color line-drawing, a color photograph, a black and white line-drawing and a black and white photograph (**Figure 4.1**). The color used to create the color line-drawing version of the color diagnostic objects was selected by choosing the surface color of the correspondent color photograph and pasting the color onto the line-drawing using the color replacement tool. To ensure that the color diagnostic objects and non-color diagnostic objects were matched for color frequency and luminance, we applied the color of the color diagnostic objects to the non-color diagnostic ones. Thus, the color version of a non-color diagnostic image (both photographs and line-drawings) was created by selecting the surface color of a color diagnostic object and pasting that color onto the non-color diagnostic object using the color replacement tool. The luminance of the color-replaced image was adjusted using the brightness tool. The colored images (line-drawings and photographs) of both color diagnostic and non-color diagnostic objects were converted to grayscale using the grayscale mode, which preserves the luminance while discarding the color. We did not find any difference in the luminance values between the four versions of the diagnostic and nondiagnostic items (overall $p > 0.20$). Finally, for the object verification task, we constructed a non-object version of each image. The non-objects were constructed by shape deformation using the *filter distort* feature in

Adobe Photoshop CS2. Sine waves were applied to the stimuli in a randomized fashion until it was not possible to recognize the original object shape (**Figure 4.1**).

Table 4.1. Mean (*SD*) ratings for color diagnosticity, prototypicality, familiarity, visual ambiguity and visual complexity for color diagnostic and non-color diagnostic objects.

	Color Diagnostic Objects	Non-Color Diagnostic Objects	Mann-Whitney U Test
Color Diagnosticity	4.4 (0.2)	2.3 (0.7)	Z = 7.3, $p < 0.001$
Prototypicality	4.3 (0.5)	4.3 (0.3)	Z = 1.2, $p = 0.2$
Familiarity	4.4 (0.5)	4.3 (0.4)	Z = 0.3, $p = 0.7$
Visual ambiguity	2.4 (0.8)	2.2 (0.7)	Z = 0.5, $p = 0.6$
Visual complexity	2.6 (0.6)	2.7 (0.6)	Z = -0.5, $p = 0.6$

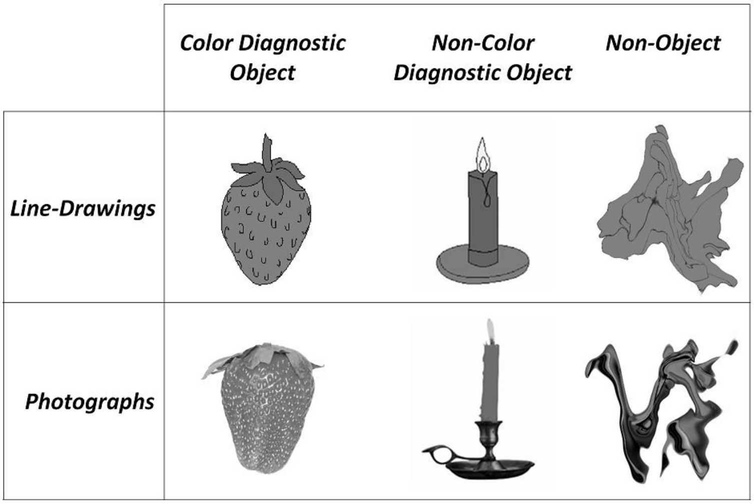

Figure 4.1. Example of the stimuli used in the experiment in the black and white presentation mode.

Procedures

Three computerized verification tasks were designed, in which a picture of an object was preceded by a word: an object verification task, in which before each picture, one of two possible words was presented: *object* or *non-object*; a category verification task, in which before each picture, either the word *biologic* or *artifact* was presented; and a name verification task, in which, before each picture, an object name was presented. In all verification tasks, participants were asked to verify whether or not the presented picture matched the previously presented word. Each participant performed the three verification tasks (the presentation order was balanced across participants). The 72 objects and 72 non-objects were divided into four sets of 18 objects. In each task, four different sets of objects were randomly chosen without replacement to be presented in one of the four experimental conditions, one set for each condition. In the object verification task, four different sets of non-objects were also randomly selected (without replacement) to be presented in one of the four experimental conditions. No participant saw an object twice in the same condition.

The category verification and the name verification tasks each comprised a total of 72 trials: half of the trials were matching trials (word and picture matched) and the other half were non-matching trials (word and picture did not match). The non-object verification task included 144 trials, 72 trials with objects (50/50 matching/non-matching trials), and 72 trails with non-objects (50/50 matching/non-matching trials). In all the tasks, half of the trials were with color diagnostic objects (50/50 colored/black and white) and the other half were with non-color diagnostic object presentations (50/50 colored/black and white).A specific item appeared for half of the participants associated to a matching trial and for the other half to a non-matching trial. The Presentation 0.7 software (http://nbs.neuro-bs.com/presentation) was used to display the stimuli on a computer screen (on a laptop Toshiba screen Satellite A300; size: 17’’; spatial resolution: 1024 X 768; color resolution: 24 bits) and to register the response times. Each trial started with a fixation cross displayed in the center of the screen for 1500 ms. After the fixation cross, the word (Arial; font size 70) was presented for 1000 ms, followed by the presentation of the object picture (500 × 362 pixels) for 150 ms. The response window was 2000 ms, after which the next trial was presented.

Participants were instructed to decide as accurately and as quickly as possible whether the word and the picture matched by pressing one of the two response keys (half of the participants used the right-left hand for yes-no and the other half for no-yes). Participants were allowed a break between the tasks. Before each task, participants participated in a training session with 10 trials.

4.3 Results

The results were analyzed by subject (*F*1) and by stimulus (*F*2). A minimum *F* (min*F*) was calculated from the *F*1 and *F*2 analyses. This approach ensured that the results were generalized over both subject and stimulus domains (Clark, 1973; Raaijmakers, 2003; Raaijmakers, Schrijnemakers, & Gremmen, 1999). None of the main effects or interactions that failed to reach significance in the min*F* calculation are reported.

Overall, the participants were able to correctly verify almost all stimuli, and we focused our analysis on the verification times. We excluded the following from the analysis: verification times from incorrect responses (object verification: 3.9%, category verification: 7.9%, and name verification: 3.9%); response times corresponding to trials where participants responded two or more times (object verification: 0.1%, category verification: 0.3%, and name verification: 0.3%); response times that were greater than the response window (object verification: 0.5%, category verification: 1.3%, and name verification: 0.1%); and no-response trials (object verification: 0.1%, category verification: 0.4%, and name verification: 0.3%). The data were checked for outliers by subject and condition, and latencies outside 2.5 standard deviations from the mean for each subject and condition were also excluded from the analysis (object verification: 4.0%, category verification: 3.2%, and name verification: 3.9%). We also excluded six objects that did not show any color effect (in terms of accuracy and response time) in any of the tasks (three color diagnostic objects: *binoculars*, *cigar*, and *barrel*; and three non-color diagnostic objects: *snake*, *beret*, and *leaf*) and three participants who showed very low performance (less than 75% of correct answers in at least one of the tasks). In total, 10.1% of the response times were excluded from the analysis. A one-way analysis of variance (ANOVA) excluded object set effects ($F(3, 860) = 0.8$; $p = 0.5$). The mean correct response times and the percentage of correct responses for each condition are given in **Table 4.2**.

Verification times were analyzed with a repeated-measures ANOVA that included the within-subject/stimulus factors of task (object verification, category verification, name verification), stimulus type (line-drawings, photographs) and presentation mode (color, black and white), as well as the object color diagnosticity (color diagnostic objects, non-color diagnostic objects) as a within-subject factor in the subject analysis and a between-stimuli factor in the item analysis. The results showed a significant task effect ($F1(2, 280) = 314.6$, $p < 0.001$; $F2(2, 128) = 285.0$, $p < 0.001$; $\mathrm{min}F(2, 362) = 149.5$, $p < 0.001$). A post-hoc comparison (Tukey HSD) for the subject analysis showed that participants were faster at name verification than object and category verification ($p < 0.001$), and faster at object verification than category verification ($p < 0.001$). A primary effect of the presentation mode was also observed ($F1(1, 140) = 67.7$, $p < 0.001$; $F2(1, 64) = 34.8$, $p < 0.001$; $\mathrm{min}F(1, 142) = 22.3$, $p < 0.001$); participants were faster when the objects were presented in color compared to black and white. The two-way interaction between the presentation mode and the object color diagnosticity was significant ($F1(1, 140) = 10.4$, $p < 0.001$; $F2(1, 64) = 8.1$, $p = 0.01$; $\mathrm{min}F(1, 159) = 4.5$, $p = 0.03$). A Tukey HSD post-hoc comparison for the subject analysis showed that when objects were presented in a color version, participants were faster at verifying color diagnostic objects than non-color diagnostic objects ($p = 0.03$); however, when objects were presented in black and white, participants verified color diagnostic and the non-color diagnostic objects equally quickly ($p = 0.3$). The three-way interaction between task, object-color diagnosticity and presentation mode was marginally significant ($F1(2, 280) = 7.9$, $p < 0.001$; $F2(2, 128) = 3.2$, $p = 0.04$; $\mathrm{min}F(2, 236) = 2.29$, $p = 0.10$; see **Table 4.2** and **Figure 4.2**). A Tukey HSD post-hoc comparison for the subject analysis showed that color diagnostic objects were verified equally fast in color and in black and white for the object verification task ($p = 0.2$); however, participants were faster at verifying color diagnostic objects when they were presented in color than when they were presented in black and white, both in the category verification task ($p < 0.001$) and in the name verification task ($p = 0.02$). However, the non-color diagnostic objects were verified faster when they were presented in color than in black and white in the object verification task ($p = 0.003$). However, both in the category and in the name verification tasks, participants verified non-color diagnostic objects equally fast when they were presented in color and in black and white ($p > 0.9$).

To avoid misinterpretation of the data and possible confusion between object color diagnosticity and semantic category effects (Nagai & Yokosawa, 2003), we explored the color effects in both biological and artifact objects independently. The mean correct response times and the percentage of correct responses for each condition are given in **Table 4.3**. A repeated-measures ANOVA was performed that included the semantic category (biologic, artifacts) as a within-subject factor in the subject analysis and a between-stimuli factor in the item analysis, and task (object verification, category verification, name verification) and presentation mode (color, black and white) were considered a within-subject/stimulus factors. The results showed a significant semantic category effect ($F1(1, 140)=138.1$, $p < 0.001$; $F2(1, 64) = 102.3$, $p < 0.001$; $\min F(1, 155) = 58.8$, $p < 0.001$); participants were quicker at responding to the biological items than to the artifact items, which was a main effect of task ($F1(2, 139) = 267.7$, $p < 0.001$; $F2(1, 63) = 897.6$, $p < 0.001$; $\min F(1, 196) = 206.2$, $p < 0.001$). A post-hoc comparison (Tukey HSD) for the subject analysis showed that participants were faster at name verification than object and category verification ($p < 0.001$), and object verification was performed faster than category verification ($p < 0.001$). A primary effect of presentation mode ($F1(1, 140) = 73.6$, $p < 0.001$; $F2(1, 64) = 32.4$, $p < 0.001$; $\min F(1, 122) = 22.5$, $p < 0.001$) was observed; participants were faster at responding to color objects compared to black and white objects. The two-way interaction between semantic category and task was also significant (*F*1(2, 139) = 267.7, *p* < 0.001; *F*2(2, 63) = 897.6, *p* < 0.001; min*F*(1, 170) = 52.2, *p* < 0.001); a post-hoc comparison (Tukey HSD) for the subject analysis showed that participants verified biological and artifact items equally quickly in the object and in the name verification tasks (*p* > 0.9); however, participants were faster at verifying biological than artifact objects in the category verification task (*p* = 0.03). Note that none of the interactions between category and color reached a significant level.

Table 4.2. Mean response time (*SD*) and percentage of correct responses (*SD*) for color diagnostic objects (CDO) and non-color diagnostic objects (NCDO) in each presentation mode and for the three verification tasks.

	Verification Task					
	Object		**Category**		**Name**	
	RT (*SD*)	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**
CDO						
Color	663 (127)	96 (7)	730 (135)	92 (10)	521 (122)	97 (5)
Black and White	687 (132)	96 (8)	784 (151)	92 (9)	551 (125)	95 (7)
NCDO						
Color	652 (118)	96 (8)	770 (13)	92 (11)	532 (125)	96 (7)
Black and White	686 (12)	97 (7)	767 (12)	90 (12)	542 (128)	96 (7)

Table 4.3. Mean response time (*SD*) and percentage of correct responses (*SD*) for natural object (NO) and artifact objects (AO) in each presentation mode and for the three verification tasks.

	Verification Task					
	Object		**Category**		**Name**	
	RT (*SD*)	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**	**RT (*SD*)**	**% (*SD*)**
NO						
Color	664 (127)	96 (7)	674 (130)	96 (9)	521 (124)	97 (7)
Black and White	685 (140)	95 (8)	716 (133)	95 (8)	552 (123)	95 (9)
AO						
Color	655 (127)	96(7)	848 (174)	87 (13)	534 (128)	97 (7)
Black and White	687(140)	97(8)	856 (178)	88 (14)	541 (132)	96 (8)

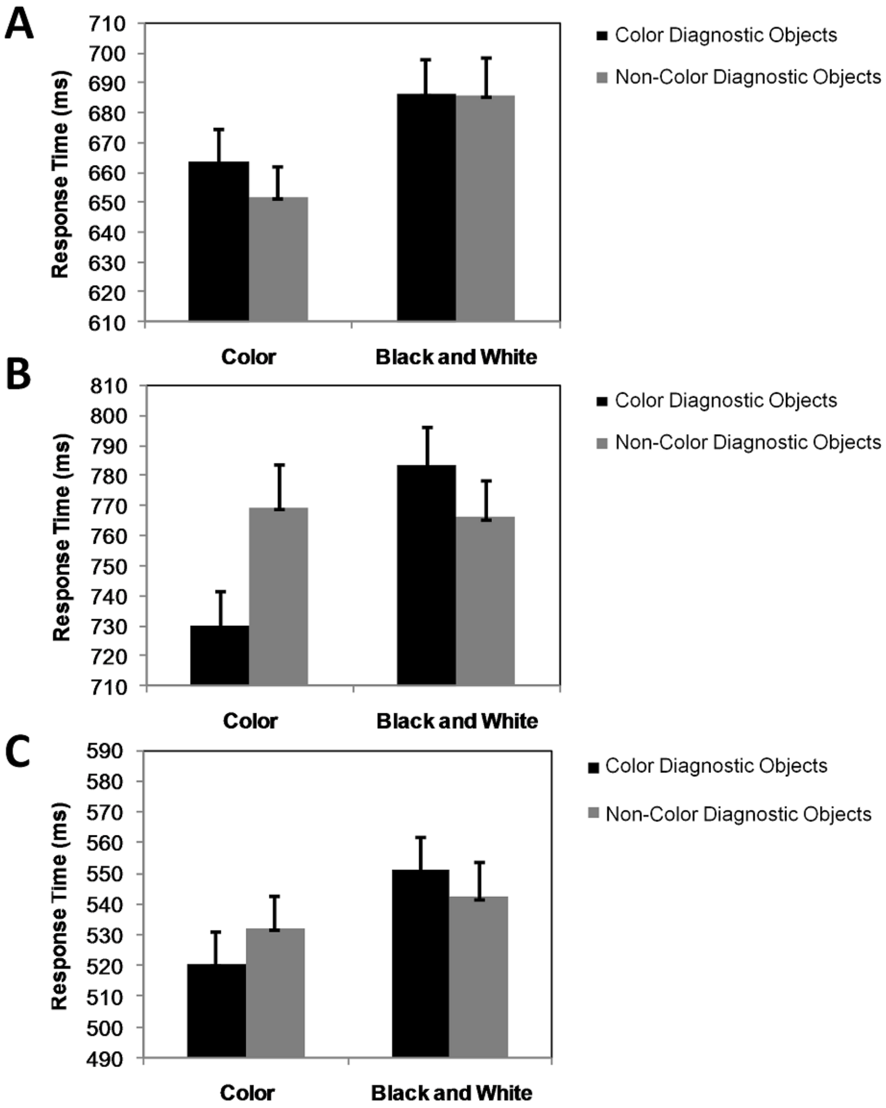

Figure 4.2. Three-way interaction between the factors task, diagnosticity color object and presentation mode on verification times. A – Object verification task, B – Category verification task, C – Naming verification task. Bars represent standard error.

4.4 Discussion

In this study, we investigated the level of visual processing at which perceptual information determined by input color facilitates the recognition process of color diagnostic and non-color diagnostic objects. We hypothesized that perceptual color information modulates the recognition of color diagnostic and non-color diagnostic objects at different processing stages. Specifically, we hypothesized that color information improves the recognition of color diagnostic objects both at the early visual stages and at the semantic level. In contrast, we proposed that the recognition of the non-color diagnostic objects is only modulated at early visual processing stages; color information supports the encoding of the object shape, which facilitates access to the structural description. Consistent with our predictions, the results showed that color facilitates categorization and name verification of color diagnostic objects. This result shows that the main role of color information in the recognition of color diagnostic objects is to facilitate access to semantic object knowledge. The presence of the correct perceptual color is likely to trigger the activation of the semantic color knowledge, and this in turn, propagates through the semantic network. It was recently shown that color input is an important cue that triggers semantic knowledge related to object color, and this facilitates object recognition (Bramão, Faísca, Petersson, & Reis, 2010). Further research is needed to explore whether additional semantic knowledge (e.g., functional properties) are also activated more quickly in the presence of the correct perceptual color information. There is some evidence that this is the case. A previous FMRI study showed that colored objects activate a neural network related to visual semantic information, which is more extensive than that for black and white objects (Bramão, Faísca, Petersson, & Reis, 2010).

The color effects in the color diagnostic object recognition were not restricted to category verification; name verification was also faster in the presence of perceptual color information. However, the color effect in this task was not greater than in category verification, suggesting that color information does not contribute specifically to retrieving the object name. In other words, it appears that color input triggers the relevant semantic information, which results in faster lexical access. Consistent with this, previous evidence showed that semantic color knowledge served as a link between object shape and object name; this resulted in faster access to the name representation when activated (Davidoff, Walsh, & Wagemans, 1997; Tanaka, Weiskopf, & Williams, 2001). However, contrary to our predictions, we did not observe a significant effect of color information for the color diagnostic objects on the object verification task. Although, the color diagnostic objects were verified 24 milliseconds faster when the objects were presented in color (compared to black and white), this result was not significant. This nonsignificant result might suggest that the main role of perceptual color information in color diagnostic object recognition is not localized at the structural description level. Instead, our results show that the main role of color is taking effect at the semantic level, facilitating the activation of the semantic object network, which then results in faster lexical access. Color information may have a minor role in the recognition of color diagnostic objects at the structural description level, facilitating the extraction of the shape information and template matching in long-term memory.

In contrast, for non-color diagnostic objects, the perceptual color effect was limited to object verification. This suggests that the role of perceptual color in non-color diagnostic object recognition is restricted to early visual processes, including the matching of shape extraction for the structural description with the forms stored in long-term memory. We did not observe any effect of perceptual color information for the non-color diagnostic objects on the category and name verification tasks. We noted that to succeed on these tasks, participants also had to extract and encode shape information. Nevertheless, other cognitive demands were involved; in particular, access to stored semantic information. Because color information has a limited role or no role at all in accessing the semantic information of the non-color diagnostic objects, the effect of color on shape extraction might be masked in these tasks. This would explain why, in some studies, no color effect was observed in the naming and categorization of non-color diagnostic objects (Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999). Studies that showed an advantage of perceptual color information on object recognition also demonstrated that the improvement is greater for color diagnostic objects compared with non-color diagnostic objects (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006).

Another interesting finding was that the observed color effect was the same for line-drawings and photographs. It might seem intuitive that color would have a greater effect if it were combined with the additional surface information present in the photographs (e.g., texture and shadow), leading to faster recognition of photographs. However, this was not the case. Similar results were reported by Price and Humphreys (1989); in a naming and a categorization task, they observed that surface color and the effects of photographic detail combined subadditively, so that the combined effects were not reliably greater than either effect individually. This result suggests that both color and texture and brightness information are processed during the same time window and that both contribute independently to object recognition. The present results extend these findings. Our results show that perceptual color information is an important cue for recognizing types, as well as tokens, not only in naming and categorization tasks, but also in object decision tasks. In addition, line-drawings and photographs were recognized equally fast in our study; however, previous studies have shown that photographs tend to be recognized faster than line-drawings (Brodie, Wallace, & Sharrat, 1991; Price & Humphreys, 1989). This discrepancy might be explained by the fact that our line-drawings contained more surface details than those used in previous studies.

Previous studies have suggested that perceptual color information facilitates the recognition of natural objects but not artifacts (Price & Humphreys, 1989). However, Nagai and Yokosawa (2003) found that regardless of the semantic category, perceptual color information facilitates recognition. Consistent with the latter results, our findings are not explained by the semantic category of the objects. We found that perceptual color improves the recognition of both natural objects and artifacts in similar ways. In addition, we found that participants responded faster to natural objects than to artifacts in the category verification task. The advantage of the natural objects is in agreement with studies on category-specific effects in healthy participants. The category-specific literature on healthy participants predicts better performance with natural objects when the viewing conditions are optimal and demands for structural differentiation are low – that is, when participants do not need to select a specific representation from long-term memory (Gale, Laws, & Foley, 2006; Gerlach, 2009; Riddoch & Humphreys, 1987a).

An unexpected result in this study was the effect of task. It was thought that of the three tasks, name verification would pose the greatest cognitive challenge. Therefore, one might have expected that participants would take a longer time to respond in this task than in the other two tasks. However, this was not the case. Participants were faster at name verification compared to object verification and category verification. One possible explanation for this might be related to the labels that appeared before the stimuli in the semantic and object verification tasks: *biological* and *artifact* in category verification and *object* and *non-object* in object verification, which are more abstract concepts than object names. Moreover, it is well-known that perceptual categorization at the basic level (e.g., dog) is faster than categorization at more superordinate (e.g., animal) or subordinate levels (e.g., poodle; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). A similar effect might play a role here: participants were faster verifying the object name (e.g., strawberry) than its superordinate category (natural *versus* artifact).

Previous studies have suggested that color information is important for early visual processing (Davidoff, Walsh, & Wagemans, 1997; Gegenfurtner & Rieger, 2000; Wurm, Legge, Isenberg, & Luebker, 1993) and/or at a semantic level, where stored semantic knowledge provides an associative link between a representation of the object shape and the object name (Davidoff, Walsh, & Wagemans, 1997; Tanaka, Weiskopf, & Williams, 2001). There is also evidence showing that stored knowledge of an object's color plays a role in that object's identification (Joseph, 1997; Joseph & Proffitt, 1996; Mapelli & Behrmann, 1997). Our results show that the role of perceptual color in object recognition of color diagnostic and non-color diagnostic objects is different and depends on color diagnosticity. Perceptual color information facilitates the recognition of the color diagnostic objects at the semantic level of visual processing, while it facilitates the recognition of the non-color diagnostic objects at the level of structural description, an earlier stage of visual processing.

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Chapter 5

Electrophysiological evidence for color effects on the recognition of color diagnostic and non-color diagnostic objects

Based on:

Bramão, I., Francisco, A., Inácio, F., Faísca, L., Petersson, K. M., & Reis, A. (submitted). Electrophysiological evidences of the color effects on the recognition of color diagnostic and non-color diagnostic objects.

Abstract

In this study, we investigated the level of visual processing at which surface color information improves the recognition of color diagnostic and non-color diagnostic objects. Continuous electroencephalograms were recorded while participants performed a visual object recognition task in which colored and black-and-white versions of both types of objects were presented. Two groups of event-related potentials (ERPs) associated with color and black-and-white presentations were compared: (1) the N1 component, an index of early visual processing and (2) the N350 and N400 components, which index late visual processing. Over left occipital sites, the N1 component was modulated by color for both color and non-color diagnostic objects. In addition, for color diagnostic objects, a color effect was observed in the N350 and N400 ERP components. Our results suggest that color information is important in the recognition of color and non-color diagnostic objects at different levels of visual processing. Our interpretation is that the visual system uses color information during the recognition of both types of objects at early visual stages but only for the color diagnostic objects during late visual processing stages.

5.1 Introduction

There is a large body of evidence suggesting that color information plays a role in object recognition (for a revision, see Tanaka, Weiskopf, & Williams, 2001). However, the processing stage at which this occurs and the types of objects that might be better identified by the processing of color information are both still matters of debate. Attempts to address these issues have primarily focused on color diagnosticity, which refers to the degree to which a particular object is associated with a specific color. For example, a strawberry – a color diagnostic object – is strongly associated with the color red, whereas a comb – a non-color diagnostic object – is not associated with any specific color. While some authors report that color information improves object recognition independent of color diagnosticity (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006), other results suggest that color improves the recognition of only color diagnostic objects (Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999).

In a previous behavioral study, we 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 (Bramão, Inácio, Faísca, Reis, & Petersson, 2011). In this study, we built upon these behavioral results through the use of electroencephalogram (EEG) recording. Unlike behavioral measures, event-related potentials (ERPs) allow for the analysis of electrophysiological signatures of cognitive processes with a temporal resolution of milliseconds. This represents an optimal approach to investigate the level of visual processing at which surface color modulates object recognition. For example, in a recent ERP study, Lu and collaborators (Lu et al., 2010) investigated the impact of color information in object recognition and found that color effects could be detected in the early ERP components that index visual perceptual processing (including N1, P2 and N2). In addition, they found a color modulation of a late visual component associated with semantic processing (N350). These findings provide evidence that, during object recognition, color information is important at both the perceptual and semantic level. However, Lu and colleagues only used color diagnostic objects, making it difficult to distinguish the potentially different roles for color during the recognition of color and non-color diagnostic objects (Lu et al., 2010).

In this study, we recorded ERPs during a visual recognition task in which colored and black-and-white versions of color and non-color diagnostic objects were presented. The differences between color and black-and-white presentations were investigated with respect to the early visual N1 component and the two late visual N350 and N400 components. The N1 component peaks at approximately 150 ms after stimulus onset is observed primarily over the occipito-temporal region, and it is an electrophysiological index of perceptual processing, where increased visual processing demands are reflected by 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 findings, we predicted that the ERPs associated with black and white stimulus would elicit a more negative N1 response in occipital sites compared to color stimuli for both types of objects.

The N350 and N400 components are ERPs related to semantic processing. N350 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). N350 appears specific for visual stimuli and is the first marker of successful object categorization, with increased magnitude (i.e., more negative) over frontal regions for unidentified objects compared to correctly-categorized stimuli (Hamm, Johnson, & Kirk, 2002; McPherson & Holcomb, 1999; Schendan & Kutas, 2002, 2007). N350 is followed by the N400 component, which is a negative deflection over central-parietal regions peaking at approximately 400 ms after stimulus onset. N400 has been widely used as an index of semantic processing, with an increase in magnitude (again, more negative) for semantically unrelated compared to semantically related material (Kutas & Hillyard, 1980a, 1980b). Both N350 and N400 ERP components are related to late visual processing, with N350 reflecting early object categorization (e.g., a member of a meaningful structural group) and N400 being sensitive to information extracted after initial categorization (Hamm, Johnson, & Kirk, 2002). Based on our previous work, we hypothesized that color effects in these two components would be restricted to color diagnostic objects (Bramão, Faísca, Petersson, & Reis, 2010).

5.2 Methods

Participants

Twenty-two right-handed native Portuguese speakers (mean age [± *SD*] = 24 ± 4 years, range 18-33 years; mean years of education [± *SD*] = 15 ± 1 years, range 13-17 years; 5 males and 17 females) with normal or corrected-to-normal vision participated in the study. All subjects completed health questionnaires, and none indicated a history of head injury or other neurological or psychiatric problems. All subjects read and signed an informed consent form describing the procedures in accordance with the Declaration of Helsinki guidelines. The study was approved by the local ethics committee.

Stimulus Material

The initial pool of stimuli consisted of 220 photos of common objects. Some were selected from the Focus Multimedia CD Photo Library, some from the set of Reis and colleagues (Reis, Faísca, Ingvar, & Petersson, 2006), and some via an Internet image search using the Google search engine. An independent group of 30 participants named and rated the initial set of objects according to prototypicality, familiarity, visual ambiguity, visual complexity, and color diagnosticity. Each stimulus was presented for one minute, and the participants were then asked to write down the name of the object. If they did not know the name, they were asked to choose one of the following categories: *do not know name*; *do not know* *object*; or *tip of the tongue*. Participants were next asked to evaluate the prototypicality of each object "*according to the degree that the presented picture represents a typical exemplar of the concept.*" They were also asked to rate the degree of agreement between the presented object and their mental image of the concept using a 5-point scale (1 = low agreement; 5 = high agreement). The familiarity of each stimulus was judged "according to how usual or unusual the object is in your experience", and the participants were asked to rate the concept itself, rather than the object, using a 5-point rating scale (1 = very unfamiliar; 5 = very familiar). The visual ambiguity of each stimulus was evaluated "according to how large is the group of different objects that are visually similar to the presented object", (5-point rating scale: 1 = completely non-ambiguous object; 5 = completely ambiguous object). The visual complexity was defined as "the amount of detail or intricacy of line in the stimulus", and the participants were asked to rate the stimulus itself rather than the real-life object (5-point scale: 1 = very low visual complexity; 5 = very complex picture). The color diagnosticity was defined as "the degree to which the object is associated with a specific color", and was rated on a 5-point scale (1 = low color diagnostic; 5 = a high color diagnostic). These instructions are similar to those typically used in object picture rating studies (Rossion & Pourtois, 2004; Snodgrass & Vanderwart, 1980; Ventura, 2003).

Following the analysis of the rating scores, we selected objects that showed at least 80% name agreement between participants. From those we selected, a total of 108 objects were used in the experiment. Of those, 84 matched with the Snodgrass and Vanderwart (1980) set. The objects were divided according to their color diagnosticity into a group of high-color diagnostic objects (31 from the natural categories and 23 from the artifact categories; **Appendix C**) and into a group of low color diagnostic objects (20 from the natural categories and 34 from the artifact categories; **Appendix C**). Color diagnosticity was the only difference between the two groups of objects that reached statistical significance. The mean comparisons between color diagnostic and non-color diagnostic items on the other rating variables were not significant (*p* > .10; **Table 5**).

We used Adobe Photoshop CS2 to create two versions of each object: a colored version and a black and white version. To ensure that the color and non-color diagnostic objects were matched for color frequency and luminance, we created the color version of non-color diagnostic pictures by using the color replacement tool to select and paste the surface color of color diagnostic objects. The luminance of the color-replaced (non-color diagnostic) picture was adjusted using the brightness tool. To create the black and white versions, the colored pictures of both object types were converted into grayscale, which preserves luminance while discarding color. We did not find any difference in the luminance values between the two item versions (overall *p* > 0.9).

Table 5. Mean (*SD*) ratings for color diagnosticicty, prototypicality, familiarity, visual ambiguity and visual complexity for color diagnostic and non-color diagnostic objects.

	Color Diagnostic Objects	Non-Color Diagnostic Objects	Mann-Whitney U Test
Color Diagnosticity	4.4 (0.2)	2.2 (0.7)	Z = 8.2, *p* < 0.001
Prototypicality	4.3 (0.5)	4.3 (0.3)	Z = 0.8, *p* = 0.4
Familiarity	4.3 (0.5)	4.3 (0.5)	Z = -0.1, *p* = 0.9
Visual ambiguity	2.4 (0.8)	2.2 (0.7)	Z = 0.8, *p* = 0.4
Visual complexity	2.6 (0.7)	2.7 (0.6)	Z = -0.3, *p* = 0.8

Experimental Procedures

In the visual object recognition task, objects were presented in a randomized order to each subject. Each object was presented twice, in color and in black-and-white, comprising a total of 216 trials. Half of the subjects saw the colored version of a particular object first, while the other half saw the black and white version of the same object first. Subjects were asked to attentively look at each object and then type the object name. If they did not know the name, they were asked to write one of the following: do not know name; do not know object; or tip-of-the-tongue. Presentation 0.7 software (http://nbs.neuro-bs.com/presentation) was used to display the stimuli on a computer screen (size: 19 in; spatial resolution: 1024 x 768; color resolution: 24 bits) and to register the participants' responses. Each trial started with a fixation cross (+) presented at the center of the screen for 1250 ms. The fixation cross was followed by presentation of the object picture (500 x 362 pixels) for 100 ms. Next, a white screen was presented for 1250 – 1750 ms, followed by the instruction to type the object name. During this period, subjects were allowed to blink their eyes. When subjects were satisfied with their answer, they pressed a key to continue the experiment and to initiate the next trial. The subjects were instructed to fixate on the center of the screen and to avoid eye blinks and body movements during the recording session. Before the task, subjects were allowed ten practice trials in order to be adequately familiarized with the experimental tasks.

EEG Recordings

Continuous electroencephalogram (EEG) was recorded from 64 Ag/AgCl active electrodes held in place on the scalp by an elastic cap. The electrode montage included 10 midline sites and 27 sites over each hemisphere. Two additional electrodes (CMS/DRL nearby Pz) were used as an online reference (for a complete description, see biosemi.com; Schutter et al., 2006). Three other electrodes were attached over the right and left mastoids and below the right eye (to monitor eye movements and blinks). Bioelectrical signals were amplified using an ActiveTwo Biosemi amplifier (DC-67 Hz bandpass, 3dB/octave) and were continuously sampled (24-bit sampling) at a rate of 512 Hz throughout the experiment.

ERP Data Analysis

The EEG data was analyzed using the open source software FieldTrip (Oostenveld, Fries, & Jensen, 2009; documentation and algorithms available at ru.nl/fcdonders/fieldtrip). ERP data were computed using a 1200 ms epoch (from 200 ms before to 1000 ms after the stimulus onset) that was time-locked to the onset of the stimuli. Before averaging, epochs for each subject that contained muscle and/or eye movement artifacts were excluded from the analysis, as were any trials containing incorrect responses. In total, 12.3% of the trials were excluded (2.8% incorrect; 9.5 % eye/muscle movement artifacts). The remaining trials were filtered offline, using a low-pass filter of 30 Hz and a high-pass filter of 0.01 Hz, and transformed to an average reference (eye electrodes were excluded). The 200 ms prior to the stimulus onset served as the baseline for the amplitude measurement for each channel. Separate ERP averages were calculated for each experimental condition.

To examine the color effects, we focused our analysis on the comparison of the ERPs elicited by black and white object presentations with those elicited by color object presentations for each stimuli type in three time windows after the onset of the stimuli: from 150 to 180 ms (N1), from 275 to 375 ms (N350), and from 375 to 500 ms (N400). Four-way (3 x 2 x 2 x 2) repeated-measure ANOVAs, using Greenhouse-Geisser adjusted degree-of-freedom, were conducted on the mean amplitude of these components from representative electrodes in frontal, central-parietal and occipital regions where modulations on ERPs by color were most often seen. The four factors were laterality (left, right hemisphere), lobe (frontal: F3, F4; central-parietal: CP3, CP4; occipital: O1, O2), stimulus type (color diagnostic, non-color diagnostic objects) and color (color, black and white).

5.3 Results

Participants were highly attentive while performing the task. When the objects were presented in color, subjects gave the correct response 97.6% of the time (color diagnostic objects = 96.5 ± 0.05, non-color diagnostic objects = 98.8 ± 0.02). When the objects were presented in black-and-white, the percentage of correct responses was 96.8% (color diagnostic objects = 94.9 ± 0.05, non-color diagnostic objects = 98.8 ± 0.02). Average waveforms for color diagnostic and non-color diagnostic objects for representative electrodes can be seen in **Figure 5.1** and **Figure 5.2**, respectively.

N1

ANOVA revealed a two-way interaction between lobe and diagnosticity ($F(1.6, 33.9) = 4.5$, $p = 0.03$). Planned comparisons revealed that color diagnostic objects were associated with more positive amplitudes in the frontal sites compared to the non-color diagnostic objects ($p = 0.02$). A two-way interaction between lobe and color was also found ($F(1.7, 35.6) = 8.4$, $p = 0.001$). The typical N1 response was stronger for objects presented in black and white compared with objects presented in color; black and white objects are associated with more positive amplitudes in the frontal sites ($p = 0.04$) and more negative amplitudes in the occipital sites ($p = 0.01$) compared to objects presented in color. A significant two-way interaction between laterality and color ($F(1, 21) = 4.5$, $p = 0.04$) was also found. Black and white objects were associated with more negative amplitudes than color objects in the left hemisphere ($p = 0.03$), while there were no differences between the two presentation modes in the right hemisphere. Finally, a significant three-way interaction between lobe, laterality and color was found ($F(1.6, 33.6) = 3.6$, $p = 0.04$). Black and white objects were associated with more negative amplitudes compared to color objects in the left occipital sites ($p = 0.01$); in the right hemisphere, black and white objects were associated with more positive amplitudes compared to color objects in the frontal sites ($p = 0.01$, **Figure 5.3**). There were no other significant interactions.

N350

ANOVA showed a significant three-way interaction between lobe, diagnosticity and color ($F(1.9, 39) = 3.8$, $p = 0.03$). Surprisingly, planned comparisons revealed that the typical N350 response for color diagnostic objects was smaller for objects presented in black and white than for objects presented in color; color objects were associated with a greater positivity in the frontal sites compared with black and white objects ($p = 0.02$). Non-color diagnostic objects did not show any amplitude differences in the N350 time window between color and black-and-white presentations (**Figure 5.3**). There were no additional significant interactions.

N400

ANOVA revealed a significant three-way interaction between lobe, diagnosticity and color ($F(2, 41.6) = 4.0$, $p = 0.03$). Planned comparisons showed that there were no differences in the N400 time window between color and black-and-white presentations for the non-color diagnostic objects. However, color diagnostic objects presented in black and white were associated with stronger negative amplitudes in the central-parietal sites ($p = 0.03$) and with stronger positive amplitudes in the frontal sites ($p = 0.02$) compared with color presentations. Therefore, when objects are strongly associated with a color, the typical N400 response is more robust for black and white objects when compared to color objects (**Figure 5.3**). No additional interactions were significant.

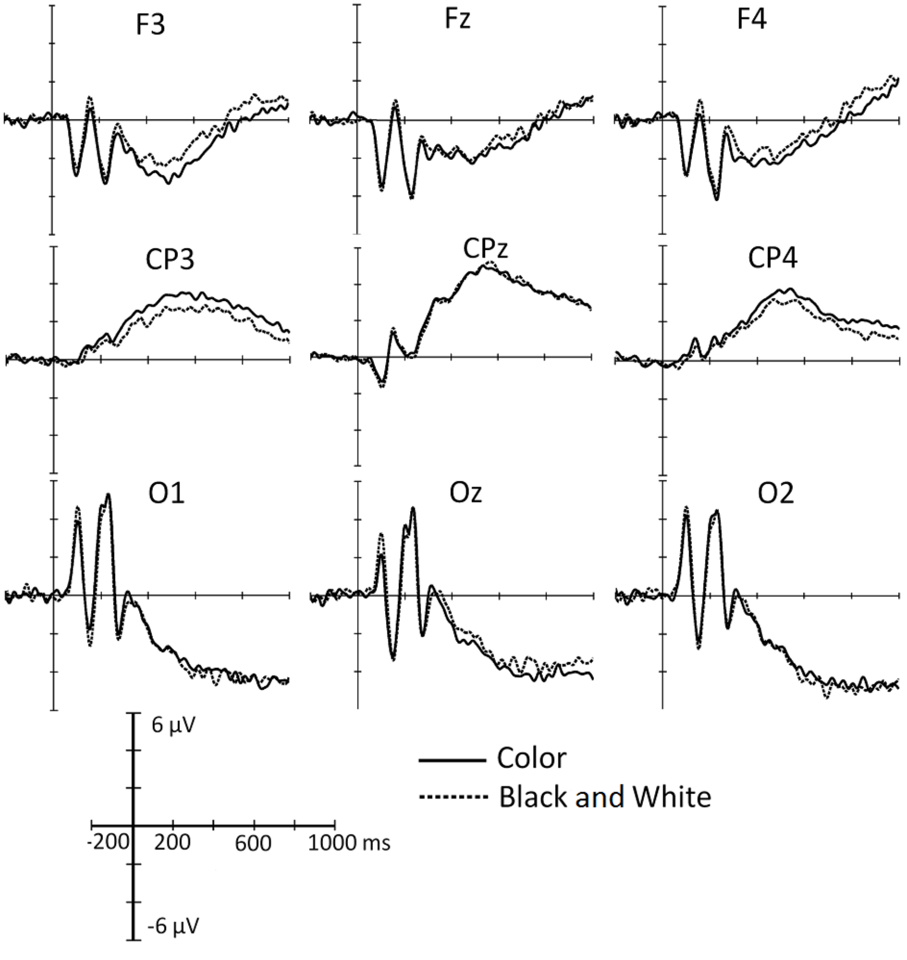

Figure 5.1. Grand average ERP waveforms at nine representative electrodes for color diagnostic object with typical color (solid line) and black-and-white (dotted line).

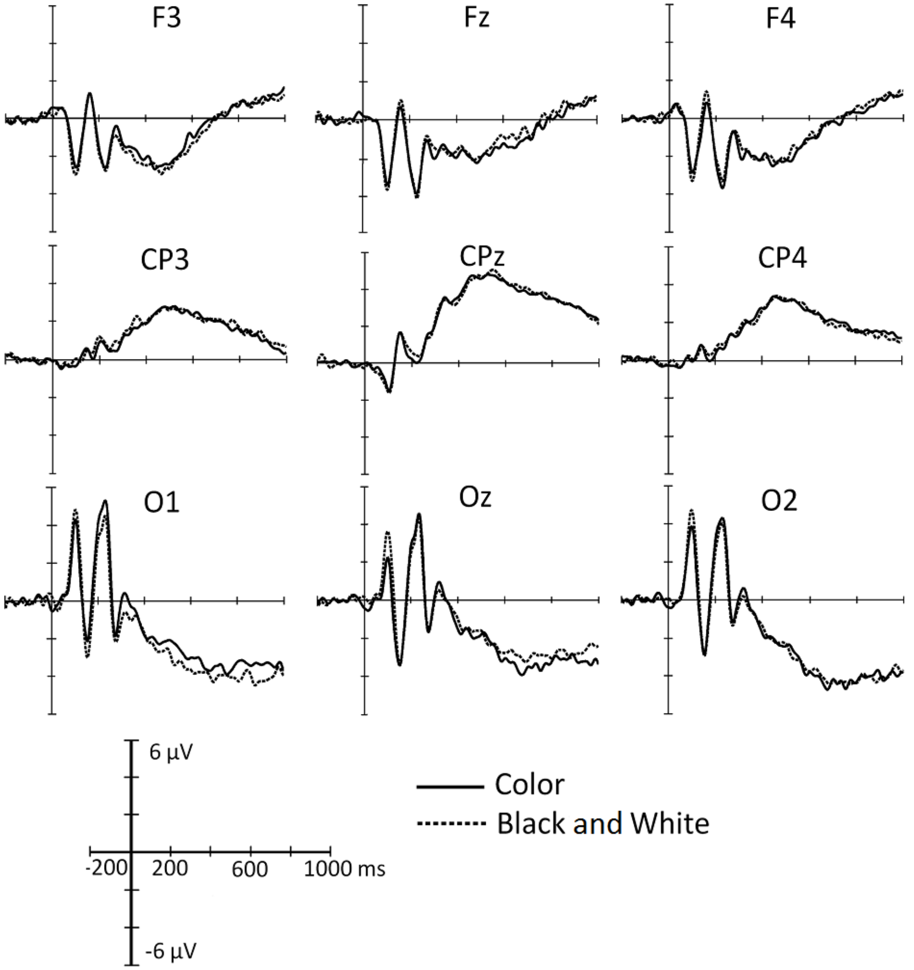

Figure 5.2. Grand average ERP waveforms at nine representative electrodes for non-color diagnostic object with typical color (solid line) and black-and-white (dotted line).

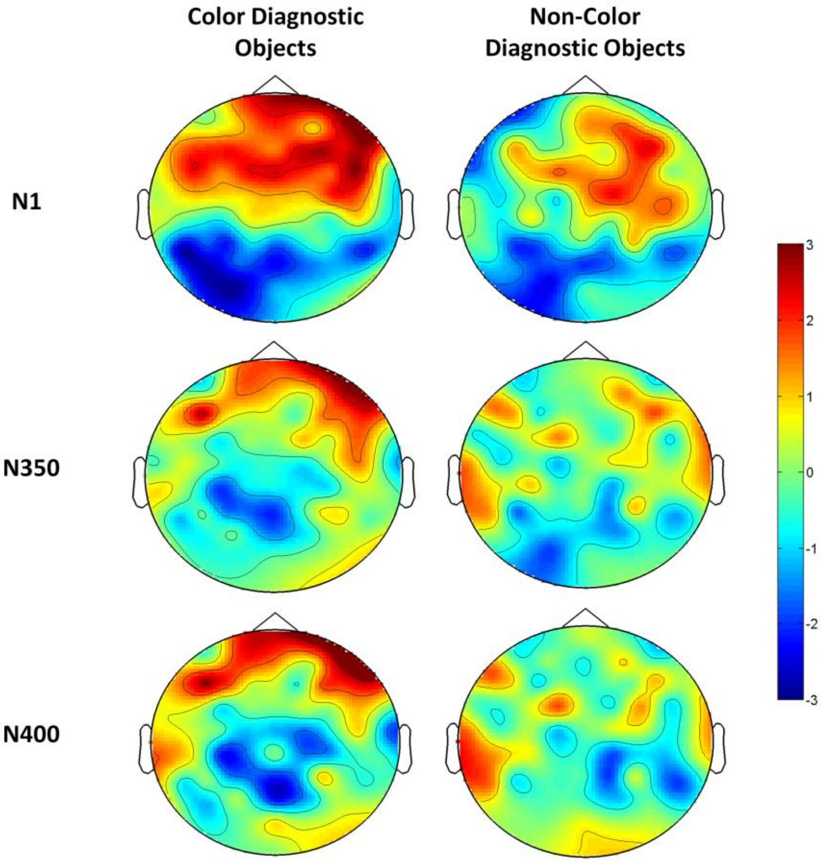

Figure 5.3. Topographic distribution of the black and white *versus* color objects in the time windows of interest for the diagnostic and non-color diagnostic objects.

5.4 Discussion

In this study, we examined the visual processing level at which color information participates in the recognition of color diagnostic and non-color diagnostic objects. ERPs were recorded during an object recognition task, in which subjects were asked to identify and name color diagnostic and non-color diagnostic objects presented in both color and black-and-white. The differences between color and black-and-white stimuli presentations were investigated with respect to one early (N1) and two late (N350 and N400) ERP components.

For both color diagnostic and non-color diagnostic objects, we observed color effects in the early N1 component, which indexes early visual processing (Jameson & D'Andrade, 1997; Kiefer, 2001; Rossion et al., 2000; Tanaka, Luu, Weisbrod, & Kiefer, 1999; Wang & Kameda, 2005; Wang & Suemitsu, 2007). Our results showed that black and white object presentations elicited a more negative response in the N1 time window compared to the color presentations, suggesting that when objects are presented in color, there is a lower demand on visual perceptual processing. Color effects in early ERPs components were previously reported for color diagnostic objects (Lu et al., 2010) and natural scenes (Goffaux et al., 2005). This study extends the previous findings by showing that the color effects in the N1 component are independent of the diagnosticity status, suggesting that color modulates the early visual perceptual stages for both color diagnostic and non-color diagnostic objects.

In addition, we found color effects for color diagnostic objects in the N350 and N400 components. The effect observed in N350 showed that color presentations are associated with stronger negative amplitudes over frontal regions compared to black and white presentations. The N350 component marks the first ERP divergence related to object categorization, showing a smaller amplitude for correctly categorized objects (McPherson & Holcomb, 1999; Schendan & Kutas, 2002). N350 also shows effects related to typicality, with a smaller amplitude for canonical views compared to uncommon, non-canonical views (Schendan & Kutas, 2007). Based on this, we would have expected that black and white object presentations would generate a larger N350 component than color presentations, suggesting that objects presented in color are more easily recognized than those presented in black-and-white. Actually, Lu and collaborators (Lu et al., 2010) found that black-and-white and atypically colored objects were associated with more negative amplitudes in this time window compared with typical color objects. In a previous color knowledge verification study, we found a similar result: atypically colored objects generated a more negative N350 component than typically colored objects, showing that the typical color object presentations are better recognized and categorized than the atypical color ones (Bramão et al., Submitted). In the present study, we did not replicate these findings, and this apparent discrepancy is most likely task-related. It is important to note that the black and white versions of our objects did not create any sort of task incongruence or interference. Instead, they served as a neutral control condition that might not have been effective enough in eliciting a greater negativity in the N350 component. Another possibility is that black and white objects are more easily recognized or identified than color objects. However, we used the same object set in a previous behavioral study and found that color object presentations are named and categorized faster than the black and white versions of the same object (Bramão, Inácio, Faísca, Reis, & Petersson, 2011). Currently, we are unable to explain the fact that color objects elicited larger N350 responses than black and white objects. Nevertheless, the important conclusion here is that the N350 component indexes generic visual knowledge and categorization and differentiates between color and black-and-white presentations for color diagnostic objects, suggesting that color information plays a role in the selection of structural descriptions that match the perceptual input.

Finally, we found an additional color effect for color diagnostic objects in the N400 component. The N400 component is an index of semantic processing; it is more negative for unrelated stimuli than for related stimuli (Hamm, Johnson, & Kirk, 2002; McPherson & Holcomb, 1999). Black and white stimuli elicited a more negative N400 response over the central-parietal region compared to the color stimuli, suggesting that, during recognition, surface color information is processed at the semantic level for the color diagnostic objects. Therefore, the presence of surface color might activate a more extensive object semantic network, facilitating object recognition. It is important to note that because we used the same set of shapes and objects counterbalanced across the color and black-and-white conditions, the observed ERP color effects can only be attributed to the nature of the color-shape associations and not to any other sensory or physical stimulus characteristic.

In summary, our ERP results confirm that, during object recognition, surface color is processed at different levels of the visual processing hierarchy. It appears that surface color is processed both at early visual perceptual and at later visual semantic stages during color diagnostic object identification, whereas the role of surface color is limited to the early visual perceptual stages for non-color diagnostic objects.

Acknowledgements

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Chapter 6

Cortical brain regions associated with color processing: An FMRI study

Based on:

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Abstract

To clarify whether the neural pathways concerning color processing are the same for natural objects, for artifacts objects and for non-objects we examined brain responses measured with functional magnetic resonance imaging (FMRI) during a covert naming task including the factors color (color *versus* black and white) and stimulus type (natural *versus* artifacts *versus* non-objects). Our results indicate that the superior parietal lobule and precuneus (BA 7) bilaterally, the right hippocampus and the right fusifom gyrus (V4) make part of a network responsible for color processing both for natural objects and artifacts, but not for non-objects. When color objects (both natural and artifacts) were contrasted with color non-objects we observed activations in the right parahippocampal gyrus (BA 35/36), the superior parietal lobule (BA 7) bilaterally, the left inferior middle temporal region (BA 20/21) and the inferior and superior frontal regions (BA 10/11/47). These activations were not found when black and white objects were contrasted with black and white non-objects, suggesting that colored objects recruit brain regions that are related to visual semantic information/retrieval and brain regions related to visuo-spatial processing. Overall, the results suggest that color information is an attribute that participates in the recognition of natural objects and artifact activating a specific neural network related to visual semantic information.

6.1 Introduction

Traditionally, theories about object recognition have emphasized the role of shape information in higher-level vision (Biederman, 1987; Biederman & Ju, 1988). More recently, data from behavioral studies, neuroimaging, and neuropsychological studies have suggested that surface features, such as color, also contribute to object recognition (for a review, see Tanaka, Weiskopf, & Williams, 2001). However, the conditions under which surface color improves object recognition are not well understood. One general idea is that surface color improves the recognition of objects from natural categories, but not the recognition of artifact categories (Humphreys, Goodale, Jakobson, & Servos, 1994; Mapelli & Behrmann, 1997; Price & Humphreys, 1989). Humphreys and colleagues showed that objects from structurally similar categories, such as natural objects, take longer to identify than items from structurally dissimilar categories, such as artifacts, because the representations of structurally similar objects are more likely to be co-activated, therefore resulting in greater levels of competition within the object recognition system. Apparently, surface details such as color can help in resolving this competition (Humphreys, Price, & Riddoch, 1999; Humphreys, Riddoch, & Quinlan, 1988; Riddoch & Humphreys, 1987b). Another potential reason that color information might help in recognizing natural objects is color diagnosticity. Color diagnosticity means the degree to which a particular object is associated with a specific color. Several experiments have shown that visual recognition of color diagnostic objects benefits from surface color information, whereas recognition of non-color diagnostic objects does not (Nagai & Yokosawa, 2003; Oliva & Schyns, 2000; Tanaka & Presnell, 1999). Typically, natural objects are more strongly associated with a specific color than artifacts. For example, a strawberry – a color diagnostic object – is clearly associated with the color red, whereas a comb – a non-color diagnostic object – is not strongly associated with any specific color when using color as a cue for object identification (Price & Humphreys, 1989). Nagai and Yokosawa (2003) studied the interaction between color diagnosticity and semantic category in order to determine whether surface color helps in the recognition of color diagnostic objects independently from their semantic category. In a classification experiment, surface color improved the recognition of color diagnostic objects independently from their category, supporting the hypothesis that color diagnosticity is an important cue for object recognition.

In this study, we used functional magnetic resonance imaging (FMRI) to investigate whether color information plays a different role in the recognition of natural objects compared to artifacts. We examined FMRI responses during a naming task that involved natural objects and artifacts presented in both color and black-and-white. The color diagnosticity was kept constant between the two categories (Rossion & Pourtois, 2004). If color information plays a different role in the recognition of artifacts compared to natural objects, then different brain regions should be engaged during the naming of colored objects from different categories.

The neural correlates of color processing have been thoroughly investigated. Previous functional neuroimaging studies have associated area V4, located within the fusiform gyrus, as a centre of color perception in the human brain (Bartels & Zeki, 2000; Conway, Moeller, & Tsao, 2007; Conway & Tsao, 2006; Lueck et al., 1989; McKeefry & Zeki, 1997; Murphey, Yoshor, & Beauchamp, 2008; Zeki et al., 1991). At the neuroanatomical level, area V4 is involved in color constancy operations (Barbur & Spang, 2008; Bartels & Zeki, 2000), color ordering tasks (Beauchamp, Haxby, Jennings, & DeYoe, 1999), object color recognition (Chao & Martin, 1999; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Zeki & Marini, 1998), conscious color perception (Morita et al., 2004), color imagery (Howard et al., 1998) and color knowledge (Simmons et al., 2007). Whereas V4 has been associated with color perception, the left inferior temporal gyrus has been described as the site of stored information about color knowledge (Chao & Martin, 1999; Kellenbach, Brett, & Patterson, 2001). For example, Chao and Martin (Chao &

Martin, 1999) argue that the cortical areas that subserve color knowledge are distinct from the cortical areas that subserve color perception.

With regard to colored object recognition, Zeki and Marini (1998) found that both naturally and unnaturally colored objects activated a pathway extending from the posterior occipital V1 to the posterior fusiform V4. In addition to the posterior parts of the fusiform gyrus, naturally colored objects activated the medial temporal lobe and the ventrolateral prefrontal cortex. These results suggest three broad cortical stages for color processing. The first stage is based in V1, and possibly V2, and is mainly concerned with registering the presence and intensity of different wavelengths and wavelength differences. The second stage, supported by V4, involves automatic color constancy operations and is independent from memory operations, perceptual judgment or learning. The third and final stage, based in the inferior temporal and frontal cortices, processes information for naturally colored objects and involves memory, judgment and learning (Zeki & Marini, 1998).

One question of interest in this context is the role of surface color when color is a property of an object compared to when color is part of an abstract composition or a non-object. According to the three-stage model for color processing outlined by Zeki and Marini (1998), colored natural objects and artifacts should engage brain regions involved in the third stage of color processing, whereas colored non-objects should only engage brain regions involved in the first two stages. To address this issue, in addition to natural objects and artifacts, we included non-objects presented in color and in black and white.

In summary, in the present FMRI study, we investigated whether the neural correlates of color information are the same for natural objects and artifacts. We also assessed the brain regions that are specific for color when color is a property of a recognizable object compared to when color is part of an unrecognizable composition. To address these issues, we examined FMRI responses in a silent naming task with two factors: color (color *versus* black and white) and stimulus type (natural objects *versus* artifacts *versus* non-objects). We expected to find fusiform gyrus (V4) activation in the color *versus* black and white stimuli (for both objects and non-objects), confirming that the fusiform gyrus is the brain center for color perception. Additionally, we hypothesized that colored natural objects and artifacts would engage brain regions involved with color knowledge information and retrieval (inferior temporal and frontal activations) to a greater degree compared with black and white natural objects and artifacts.

6.2 Methods

Participants

Twenty right-handed Portuguese native speakers (mean age [± *SD*] = 22 ± 4 years, range 19-32 years; mean years of education [± *SD*] = 14 ± 1 years, range 13-18 years; 5 males and 15 females) with normal or corrected-to-normal vision participated in the study. All subjects completed health questionnaires prior to scanning, and none reported a history of head injury or other neurological or psychiatric problems. All subjects read and signed an informed consent form describing the procedures according to the Declaration of Helsinki. The study was approved by the local ethics committee.

Stimulus Material

We selected 56 drawings from the Snodgrass and Vanderwart set (1980). Twenty-eight objects were from natural categories (animals and fruits) and twenty-eight were artifacts (tools and vehicles; see **Appendix D**). We also constructed 28 matching non-objects (constructed with the Paint-software and approximately matched for visual complexity). The non-objects were scrambled lines and shapes without any obvious conventional meaning. All images were presented both in color and black-and-white. The color version was selected from the set of Rossion and Pourtois (2004) and the black and white version was selected from the gray-scale set of Rossion and Pourtois (2004). We opted for the gray-scale version and not the original black and white version from the Snodgrass and Vanderwart (1980) set in order to keep the luminance and brightness constant over the color and black-and-white conditions. All 56 images were classified according to familiarity based on norms for the Portuguese population (Ventura, 2003), color diagnosticity based on Rossion and Pourtois (2004), and visual complexity based on the original work of Snodgrass and Vanderwart (1980). There was no significant difference between stimulus types on these variables ($p > 0.1$). In addition, the natural and artifact stimuli were matched in terms of syllabic length ($p > 0.2$). Stimuli luminance, measured using Adobe Photoshop 7.0, of the natural objects, artifacts and non-objects (color and black-and-white versions) was similar (overall, $p > 0.5$).

Experimental Procedures

The stimuli were presented in a blocked design. The twenty-eight stimuli from each condition were distributed over four blocks (6 conditions x 4 blocks; seven objects in each block) resulting in twenty-four blocks. Four of each condition were allocated to two different sets (each set was composed of 84 stimuli grouped into two blocks for each condition – 2 blocks x 6 conditions x 7 stimuli). Two additional sets were constructed by changing the presentation order of the blocks in the two original sets. In each experimental set, we also included four blocks of seven baseline events, consisting of a visual fixation cross. For each subject, four sets were presented in four consecutive FMRI sessions. Altogether, 112 objects were presented to each subject per FMRI session, which included the seven experimental conditions: CN – colored natural objects, BWN – black and white natural objects, CA – colored artifacts, BWA – black and white artifacts, CNO – colored non-objects, BWNO – black and white non-objects, and finally VF – visual fixation, which served as a baseline condition. Each subject saw each object twice per condition during the experiment, but never in the same FMRI session. Each block lasted 19.6 seconds, and each stimulus was presented for 2.8 seconds (**Figure 6.1**).

In four separate scanning sessions, with session order counterbalanced across subjects, subjects were asked to attentively view the picture and silently name each object, in a covert naming task. Each of the four FMRI sessions lasted 6 minutes. Subjects were also asked to silently repeat "*tan-tan"* for the non-objects and for the visual fixation cross in order to encourage attention to the stimuli without attaching a particular verbal label. Subjects viewed the stimuli via a mirror mounted on a head-coil (the visual angle for the stimulus presentation was approximately 8 degrees). Prior to the FMRI experiment, subjects performed an object naming task in order to familiarize themselves with the objects and for the acquisition of behavioral naming data. The verbal responses and naming times were registered for subsequent behavioral analysis. Voice detection equipment was used to register response times between the onset of the stimulus display and that of the response. The same presentation paradigm was used for the object naming task as for the FMRI experiment. The Presentation 0.7 Software (http://nbs.neuro-bs.com/presentation) was used to display the stimuli on a computer screen (HP Laptop with 15" screen) and to register the response times.

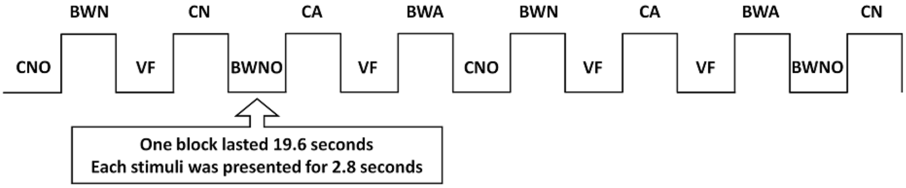

Figure 6.1. Schematic representation of the experimental design for one FMRI session. CN – color natural objects, BWN – black and white natural objects, CA – color artifacts objects, BWA – black and white artifacts objects, CNO – colored non-objects, BWNO – black and white non-objects, VF – visual fixation. Each block lasted 19.6 seconds and each stimulus was presented for 2.8 seconds.

MRI Data Acquisition

We acquired whole head T2*-weighted EPI-BOLD MRI data with a Philips 1.5 T Intera scanner using a sequential slice acquisition sequence (TR = 2.46 s, TE = 40 ms, 90º flip-angle, 29 axial slices, slice-matrix size = 64 x 64, slice thickness = 3 mm with a slice gap = 0.4, field of view = 220 mm, isotropic voxel size = 3.4 x 3.4 x 3.4 mm^3). Following the experimental session, high-resolution structural images were acquired using a T1-weighted 3D TFE (TE = 3.93 ms, 10º flip-angle, slice-matrix size = 256 x 256, field of view = 256 mm, 200 axial slices, slice thickness = 1.0 mm, isotropic voxel-size = 1 x 1 x 1 mm^3).

MRI Data Analysis

Image pre-processing and statistical analysis was performed using SPM5 (http://www.fil.ion.ucl.ac.uk/spm) implemented in MatLab (Mathworks, Sherborn, MA). The functional EPI-BOLD images were realigned and slice-time corrected, and the subject-mean functional MR images were co-registered with the corresponding structural MR images. These were subsequently anatomically normalized. The normalization transformations were generated from the structural MR images and applied to the functional MR images. The functional EPI-BOLD images were transformed into an approximate Talairach space (Talairach & Tournoux, 1998) as defined by the SPM5 template and spatially filtered with an isotropic 3D spatial Gaussian kernel (FWHM = 10 mm). The FMRI data were statistically analyzed using the general linear model and statistical parametric mapping (Friston et al., 1995). At the first level, single-subject fixed effect analyses were conducted. The linear model included one box-car regressor for each of the CN, BWN, CA, BWA, CNO, BWNO and VF conditions. We temporally convolved these explanatory variables with the canonical hemodynamic response function provided by SPM5. In addition, we also included realignment parameters to account for movement-related variability. The data were high-pass filtered (128 s) to account for various low-frequency effects. For the second-level random effect analysis, we generated single-subject contrast images for the CN, BWN, CA, BWA, CNO and BWNO conditions relative to VF.

We analyzed the contrast images in a two-way repeated measures ANOVA with the following factors: color type (color *versus* black and white) and stimulus type (natural objects *versus* artifacts *versus* non-objects). We analyzed the natural objects and artifacts together because there was no significant difference between these conditions, whether in color or black and white. Also, there was no significant difference in CN *versus* BWN or CA *versus* BWA (overall, $p > 0.3$). Thus, we generated single-subject contrasts for the colored objects – CO (= CN + CA) and the black and white objects – BWO (= BWN + BWA). We analyzed these collapsed contrasts in a two-way repeated measures ANOVA with the following factors: color type (color *versus* black and white) and stimulus type (objects *versus* non-objects). Statistical inference was based on the cluster-size statistic from the relevant SPM[T] volumes. In a whole brain search, the results from the random effects analyses were initially threshold at with $p < 0.005$ (uncorrected) and only significant clusters at $p < 0.05$ (family-wise error (FWE) corrected for multiple non-independent comparisons) are reported (Worsley et al., 1996). All local maxima within significant clusters were subsequently reported with *P*-values corrected for multiple non-independent comparisons based on the false discovery rate (FDR, Genovese, Lazar, & Nichols, 2002). SPM[T] volumes were generated to investigate the effects of color and stimulus type. Finally, we applied a small volume correction (SVC, 5 mm radius) to regions typically involved in color perception: the fusiform gyrus (V4; [± 28, -62, -20]) and the hippocampus ([± 36, -10, -20]) bilaterally (Chao & Martin, 1999; Zeki & Marini, 1998) and in a region in the left temporal gyrus previously described as the site of stored information about colored objects ([-56, -40, -14]; Chao & Martin, 1999; Kellenbach, Brett, & Patterson, 2001). All reported data are from the second-level random effect analyses. For portability of the results, we used the Talairach nomenclature (Talairach & Tournoux, 1998) with the original SPM coordinates in the tables.

6.3 Results

Behavioral Results

Subjects were able to correctly name all stimuli. Overall, the number of naming errors was small (< 2%), so we analyzed the naming times for the correct responses with latencies within 2.5 standard deviations from the mean for each subject and condition. Excessively long or short naming latencies were excluded from further analysis because these are likely due to lapses of attention/concentration and anticipatory responses, respectively. No-response trials and misregistered responses (software failure and responses anticipated by subject vocalizations other than the naming responses) were also excluded. In total, approximately 11% of the trials were excluded (3.8% due to lapses of attention or concentration, 1.6% due to anticipatory responses, 1.5% due to incorrect responses, 0.1% due to non-answers, 3.8% due to misregistered responses). The naming times were analyzed with a repeated-measures ANOVA considering the following within factors: presentation version (color *versus* black and white) and semantic category (natural objects *versus* artifacts). The results showed a significant presentation version effect [$F(1,19) = 30.6$, $p < 0.001$] – subjects were faster at naming color compared to black and white objects. The semantic category effect [$F(1,19) = 2.8$, $p = 0.13$] and the interaction between presentation version and category [$F(1,19) = 0.1$, $p = 0.76$] were not significant (**Figure 6.2**).

FMRI Results

Color and Black-and-white Effects

The contrast between color *versus* black and white stimuli (for both objects and non-objects) did not result in any significant activation, nor did the contrast between color non-objects *versus* black and white non-objects. However, the contrast between colored objects *versus* black and white objects (**Table 6.1**) showed a significant cluster ($p = 0.006$, FWE corrected) that encompassed the superior parietal region and precuneus (BA 7) bilaterally. To further investigate the regional effects related to color processing, we used a regions-of-interest (ROI) approach in combination with small volume correction (SVC) for the family-wise error rate. We selected regions of interest based on previous investigations that studied color effect in object recognition (Chao & Martin, 1999; Kellenbach, Brett, & Patterson, 2001; Zeki & Marini, 1998). These regions included the right/left fusiform gyrus (V4), the right/left hippocampus and the left inferior temporal gyrus. We investigated these regions in the following contrasts: 1) color *versus* black and white stimuli, 2) color *versus* black and white objects, and 3) color *versus* black and white non-objects. We found significant activations (**Table 6.2** and **Figure 6.3**) for color *versus* black and white ($p = 0.032$, SVC corrected) in the right hippocampus and for color *versus* black and white objects in the right fusiform gyrus (V4; $p = 0.011$, SVC corrected), right hippocampus ($p = 0.033$, SVC corrected) and left temporal inferior gyrus ($p = 0.037$, SVC corrected). The contrast between color *versus* black and white non-objects yielded no additional effects.

Color and Black-and-white Object Recognition

The contrast between object *versus* non-object stimuli resulted in two clusters of significant brain activation ($p < 0.001$, FWE corrected). These included the posterior occipital regions (BA 18/19), the fusiform gyrus (BA 19/37), and the inferior temporal lobe (BA 20) bilaterally (**Table 6.3** and **Figure 6.4**). The contrast between colored objects *versus* color non-objects (**Table 6.3** and **Figure 6.4**) resulted in additional activations in the right parahippocampal gyrus (BA 35/36), the inferior-superior parietal lobule (BA 7/39/40) bilaterally, and in the left inferior-middle temporal region (BA 20/21). In addition, frontal regions ($p = 0.006$, FWE corrected) were also significantly activated in colored objects *versus* colored non-objects, including the left anterior-inferior frontal region (BA 10/47) and the left superior frontal region (BA 10). The contrast between black and white objects *versus* black and white non-objects activated similar brain regions as observed in objects *versus* non-objects, however the activation pattern was more restricted and primarily observed in posterior brain regions (right: $p = 0.021$, FWE corrected; left: $p = 0.009$, FWE corrected; **Table 6.3** and **Figure 6.4**).

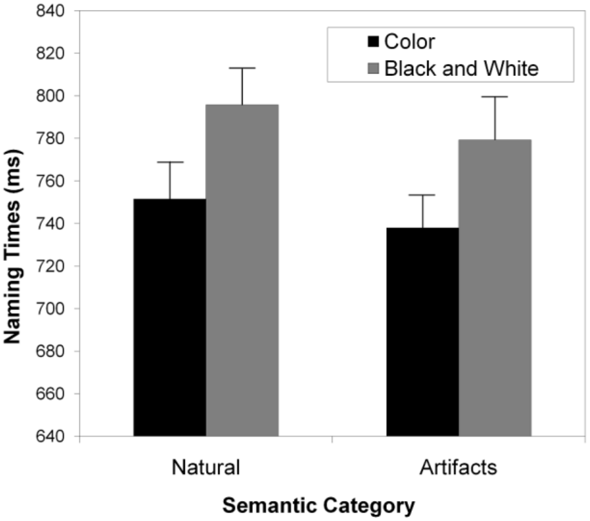

Figure 6.2. Two-way interaction between presentation version and semantic category on naming times. Bars represents standard error.

Table 6.1. Color objects and black-and-white objects.

Region	***Cluster Level***	***Coordinates***		
	P_{FWE}	***x***	***y***	***z***
Color Objects vs. Black and white Objects				
Right superior parietal (BA 7)	0.006	16	-60	64
Left superior parietal (BA 7)		-26	-64	46
Right precuneus (BA 7)		10	-48	66
Left precuneus (BA 7)		-8	-58	62

SPM [T], Clusters significant at $p < 0.05$ corrected for multiple non-independent comparisons are reported (P_{FWE}). Local maxima within the clusters are reported. Coordinated are the original SPM x, y, z in millimeters of the MNI space.

Table 6.2. Small volume corrections in SPM [T].

Region	***Voxel Lexel***		***Coordinates***		
	Z	P_{FWE}	***x***	***y***	***z***
Color *vs.* Black and white					
Right Hippocampus	2.68	0.032	36	-10	-24
Color Objects *vs.* Black and white Objects					
Right Fusiform (V4)	3.08	0.011	30	-66	-18
Right Hippocampus	2.67	0.033	36	-14	-22
Left Inferior Temporal Gyrus	2.62	0.037	-60	-42	-16

SPM [T], threshold at $p < 0.005$, non-corrected. P_{FWE} SVC corrected. Coordinates are the original SPM x, y, z in millimeters of the MNI space.

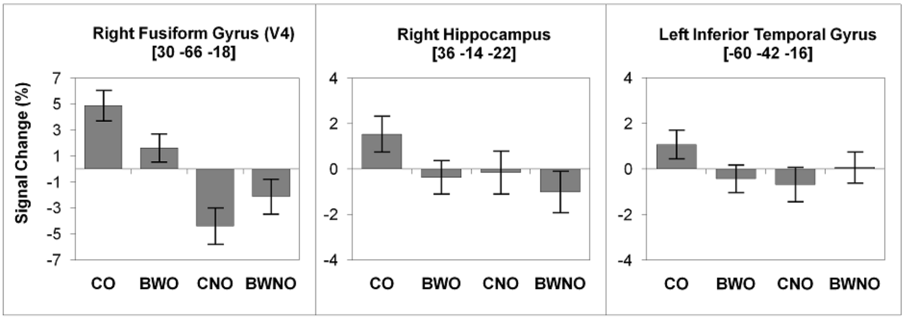

Figure 6.3. BOLD signal change associated with color and black-and-white objects (CO, BWO) and with color and black-and-white non-objects (CNO, BWNO).

Table 6.3. Objects *versus* non-objects.

Region	***Cluster Level***	***Coordinates***		
	P_{FWE}	***x***	***y***	***z***
Objects vs. Non-Objects				
Right middle occipital (BA 18/19)	< 0.001	34	-94	-6
Right fusiform (BA 19/37)		36	-66	-18
Right inferior temporal (BA 20)		48	-54	-22
Left middle occipital (BA 18/19)	< 0.001	-46	-90	-8
Left fusiform (BA 19/37)		-36	-66	-14
Left inferior temporal (BA 20)		-50	-36	-20
Objects Color vs. Non-Objects Color				
Right middle occipital (BA 18/19)	< 0.001	46	-78	-12
Right fusiform (BA 19/37)		38	-62	-20
Right parahippocampal (BA 35/36)		26	-26	-26
Right inferior temporal (BA 20)		48	-56	-18
Left middle occipital (BA 18/19)	< 0.001	-38	-86	-4
Left fusiform (BA 19/37)		-42	-60	-16
Left inferior temporal (BA 20)		-48	-60	-16
Left inferior-middle temporal (BA 20/21)		-44	-44	-18
Right inferior-superior parietal (BA 7/39/40)		26	-88	38
Right superior parietal (BA 7)		16	-90	42
Left inferior-superior parietal (BA 7/39/40)		-22	-80	42
Left superior parietal (BA 7)		-28	-62	50
Left inferior frontal (BA 11/47)	0.006	-18	42	-6
Left superior frontal (BA 10)		-20	48	8
Objects Black and white vs. Non-Objects Black and white				
Left middle occipital (BA 18/19)	0.009	-32	-100	-2
Left fusiform (BA 19/20/20)		-36	-70	-14
Right middle occipital (BA 18/19)	0.021	36	-96	-8
Right fusiform (BA 19/20/37)		36	-68	-18

SPM [T], Clusters significant at $p < 0.05$ corrected for multiple non-independent comparisons (P_{FWE}) are reported. Local maxima within the clusters are reported. Coordinated are the original SPM x, y, z in millimeters of the MNI space.

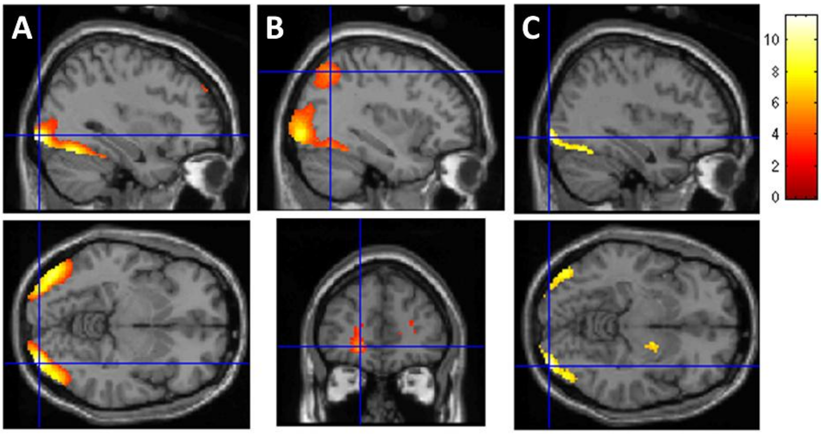

Figure 6.4. A - Brain regions associated with objects compared to non-objects, B - Brain regions associated with color objects compared to color non-objects, C - Brain regions associated with black and white objects compared to black and white non-objects.

6.4 Discussion

In this FMRI study, we aimed to clarify whether the neural substrates related to color information are the same when color is a property of a recognizable object, namely natural objects and artifacts, compared to when color is a property of an unrecognizable object, such as abstract compositions.

Color Effects on Objects and Non-Objects

According to the three cortical stages model for color processing proposed by Zeki and Marini (1998), we expected that color information presented in recognizable objects would activate the V4 area as well as brain areas involved in memory, classification, and learning operations. Our results show that color compared to black and white objects activated the right V4 area. In addition, we also observed brain activations in regions that are typically associated with color perception, the right hippocampus and superior parietal/precuneus region, corroborating previous findings (Bartels & Zeki, 2000; Chao & Martin, 1999; Howard et al., 1998; McKeefry & Zeki, 1997; Zeki & Marini, 1998; Zeki et al., 1991).

To better understand the role of color information in the recognition of familiar objects, we explored brain activation during the processing of colored objects and colored non-objects. In general, object naming activated brain regions that extended from the occipital to the inferior temporal regions, including fusiform activation, consistent with earlier neuroimaging studies on object recognition (Farah & Aguirre, 1999; Grill-Spector, 2003; Grill-Spector & Sayres, 2008; Moore & Price, 1999b; Price, Devlin, Moore, Morton, & Laird, 2005; Stiers, Peeters, Lagae, Hecke, & Sunaert, 2006; Vihla, Laine, & Salmelina, 2006). Additionally, colored objects compared to colored non-objects activated an extensive network of brain regions including the left inferior temporal gyrus, right parahippocampal gyrus, left inferior and superior parietal lobule, and left superior and anterior-inferior frontal regions. These activations were exclusive for colored objects and were not found when black and white objects were contrasted against black and white non-objects, suggesting that color plays an important role in accessing the semantic level during object naming processes, as initially suggested by Zeki and Marini (1998). We did not find any particular brain region that responded only to black and white object naming, suggesting that the recognition of black and white objects does not add a cognitive operation to the recognition of colored objects.

The temporal and frontal activations found during colored object naming suggest that color engages access to the semantic network that contains information/knowledge about the objects. Parahippocampal gyrus activation has been reported in post-recognition processes, such as visual and semantic analysis (Bar et al., 2001; Etard et al., 2000; Wiggs, Weisberg, & Martin, 1999), and during the encoding and retrieval of color information (Pulvermüller & Hauk, 2006; Ueno et al., 2007). It has been suggested that the inferior temporal gyrus stores information about colored objects (Chao, Haxby, & Martin, 1999; Kellenbach, Brett, & Patterson, 2001). The frontal activations observed during colored object naming suggest that the recognition of a colored object engages a semantic network that is more active in comparison to black and white object recognition. Left inferior frontal activations have been reported during semantic knowledge tasks (Demonet, Wise, & Frackowiak, 1993; Ganis, Schendan, & Kosslyn, 2007; Murtha, Chertkow, Beauregard, & Evans, 1999; Petersen, Fox, Posner, Mintun, & Raichle, 1988; Price, Devlin, Moore, Morton, & Laird, 2005; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996). On the other hand, the activations observed in the left inferior and superior parietal lobule might suggest that color is a feature that helps in the encoding of visuo-spatial properties of objects (Kosslyn et al., 1994; Oliver & Thompson-Schill, 2003). An alternative explanation is that the activated parietal and frontal regions during the recognition of colored objects *versus* colored non-objects results from an increase in attention due to color information (Corbetta, Patel, & Shulman, 2008). However, if this was the case, then we should have also seen this pattern of activation when colored non-objects were contrasted with black and white non-objects.

Regarding the role of color information in the processing of non-objects, we expected that color information would engage V4. However, the contrast between colored versus black and white non-objects did not yield an additional significant activation. The absence of V4 activation in the colored non-object condition might be related to methodological issues such as a lack of sensitivity or to experimental design issues. Previous studies that reported V4 activation in response to abstract colored stimuli used transient on/off presentations of each stimulus at a rate of 1 Hz (McKeefry & Zeki, 1997; Zeki & Marini, 1998).

We should point out that there are other variables that could contribute to the pattern of the observed results. In every trial, subjects had to covertly utter the name of the recognized object or utter “tan-tan” for non-objects. In the case of non-objects, subjects knew from the start of the block that they would only have to utter “tan-tan” while the block was running, without any further processing. In contrast, for object blocks, subjects had to recognize and name every object. Consequently, producing the non-sense word “tan-tan” for all non-objects did not require the same level of complexity as retrieving lexical information for certain objects. This may therefore lead to condition-dependent biases in the associated attention state, lexical retrieval and covert naming. However, when we suggest that the colored objects (*versus* colored non-objects) activated a more extensive brain network than the black and white objects (*versus* black and white non-objects), we are excluding the interference associated with attention state, lexical retrieval and covert naming because these effects are present in the contrast between both colored and black-and-white objects *versus* non-objects.

Color Effects in Natural Objects and Artifacts

Our results show that the brain regions responsible for color processing are the same when color is a property of natural objects and artifacts, suggesting that color information has the same role in the recognition of natural objects and artifacts. This result does not support the proposal of Humphreys and colleagues (Humphreys, Goodale, Jakobson, & Servos, 1994; Price & Humphreys, 1989) and suggests that previous behavioral differences reported in the processing of natural objects and artifacts might be due to color diagnosticity rather than to semantic category. When color diagnosticity is controlled, as in our study, no differences in the recognition of colored natural objects and artifacts were found in the FMRI or the behavioral results. Moreover, our results showed that the brain regions responsible for processing natural objects and artifacts are the same, both when the objects are presented in color and in black and white. Several candidate regions have emerged as potential sites that may be strongly involved in natural object recognition, including the medial occipital, right occipito-temporal and left anterior temporal cortex (Chao, Haxby, & Martin, 1999; Gerlach, Law, Gade, & Paulson, 1999; Martin, Wiggs, Ungerleider, & Haxby, 1996; Moore & Price, 1999a). On the other hand, the fusiform gyrus, left precentral gyrus and left posterior middle temporal cortex have been reported as the sites that may be strongly involved in the recognition of artifacts compared with objects from other categories (Chao, Haxby, & Martin, 1999; Martin, Wiggs, Ungerleider, & Haxby, 1996). Although category-specific brain activation patterns have been investigated in several neuroimaging studies, the results have not been consistent across studies. For example, Joseph (2001) performed a meta-analysis of stereotactic coordinates to determine if category membership predicts patterns of brain region activation across different studies. The author found no more than 50% convergence for the recognition of both natural objects and artifacts in any brain region.

Conclusions

Colored objects activate the inferior temporal, parahippocampal and inferior frontal brain regions, areas that are typically involved in visual semantic processing and retrieval. This suggests that the recognition of a colored object activates a semantic network in addition to the one that is active during the recognition of black and white objects. The engagement of the semantic network when color is present in the objects led subjects to name colored objects more quickly than black and white objects. These results suggest that color information can have an important role during the visual recognition process for familiar and recognizable objects (both natural objects and artifacts), facilitating semantic retrieval. Additionally, we did not find any particular brain region that responded only to the naming of black and white objects, suggesting that the recognition of a black and white object does not add a cognitive operation to the recognition of a colored object.

Acknowledgements

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Chapter 7

The influence of color information in object recognition: A review and meta-analysis

Based on:

Bramão, I., Reis, A., Petersson, K. M., & Faísca, L. (under revision). The influence of color information in object recognition: A review and meta-analysis. *Acta Psychologica.*

Abstract

In this study, we systematically review the scientific literature on the effect of color information on object recognition. Thirty-five independent experiments, comprising 1535 participants, were included in a meta-analysis. Overall, we found a moderate significant effect of color on object recognition (d = 0.28). The specific effects of moderator variables was also analyzed, and we found that color diagnosticity is the factor with the greatest moderator effect on the influence of color on object recognition; studies using color diagnostic objects showed a significant color effect (d = 0.43), whereas a marginal significant color effect was found in studies that used non-color diagnostic objects (d = 0.18). The present review did not permit the drawing of specific conclusions about the modulation effect of the recognition task type; while the meta-analytic review showed that color information improves object recognition specially in naming (d = 0.36), but also in semantic classification tasks (d = 0.23), the literature review revealed a large body of evidence showing positive effects of color information on object recognition in studies using a large variety of visual recognition tasks. Further research is needed to clarify this discrepancy. In addition, we found that color is important in the ability to recognize both natural and artifact objects, to recognize objects presented as types (line-drawings) or presented as tokens (photographs), and to recognize objects that are presented without other surface details, such as texture or shadow. Taken together, the results of the meta-analysis strongly support the contention that color plays a role in object recognition, suggesting that color information should be considered in models of visual object recognition.

7.1 Introduction

Traditionally, object recognition theories state that objects are recognized based on shape information, largely ignoring the potential role of color information (Biederman, 1987; Marr & Nishihara, 1978). For example, the recognition-by-components model, proposed by Biederman (1987), hypothesizes that objects are represented in terms of geons, basic geometric building blocks. This model assumes that to identify an object, the perceptual system computes a *structural description* – it determines the geons of the object and the relations among them – and in turn, this description provides access to function and meaning, as well as information about the object name. More importantly, according to the model, neither geons nor the relations among them are associated with color information or color knowledge.

More recently, a large body of behavioral, neuroimaging, and neurophysiological evidence suggests that color information contributes to object recognition, and for that reason, the role of color should be integrated in object recognition models (for a review, see Tanaka, Weiskopf, & Williams, 2001). However, although color information is now accepted to contribute to object recognition, the object properties and the viewing conditions that might benefit from color information are not well understood.

In this review and the accompanying meta-analysis, we integrate and discuss the behavioral literature on the effect of color information on object recognition as well as draw conclusions regarding the moderator role of several variables that are typically manipulated in studies that examine the influence of color on object recognition.

Color Diagnosticity

Color diagnosticity is probably the most investigated property in studies exploring the role of color information in object recognition. Color diagnosticity is defined as the degree to which a particular object is associated with a specific color. For example, a strawberry – a color diagnostic object – is clearly associated with the red color, whereas a comb – a non-color diagnostic object – is not strongly associated with any particular color. It has been proposed that color information is more important for the recognition of color diagnostic objects. Tanaka and Presnell (1999) found that colored versions of color diagnostic objects were recognized faster than uncolored versions of the same objects, while non-color diagnostic objects were recognized equally fast in color and in black and white. Similar results were reported by Nagai and Yokosawa (2003). However, other studies failed to replicate these findings and documented that color information, independent of the diagnosticity status, improves recognition (Bramão, Faísca, Petersson, & Reis, 2010; Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006; see also Biederman & Ju, 1988 and Wurm, Legge, Isenberg, & Luebker, 1993). A possible explanation for the discrepancy in the reported results is that different methods have been used to determine the color diagnosticity of an object.

Tanaka and Presnell (1999) used a very strict method to classify the color diagnosticity of a specific object. The authors used both a feature listing (where subjects were instructed to list perceptual properties of the object) and a typicality judgment task (where subjects were asked about the typical color of the object). An object was classified as a high color diagnostic object if a color was listed at the first place in the feature listing and if at least 80% of the subjects agree with the typical color of the object. A similar method was used by Nagai and Yokosawa (2003). Less strict methods were used in the other studies. For example, Biederman and Ju (1988) asked a panel of three judges to determine whether the color was or was not diagnostic for a given object. Wurm and colleagues (Wurm, Legge, Isenberg, & Luebker, 1993) provided subjects with a color name, and the subjects were asked to rate the relative symptomaticity of the color for a given object. An object was rated as high in color diagnosticity if a color was highly symptomatic of one object and not symptomatic of other objects. Rossion and Pourtois (2004) asked a group of subjects to rate objects on a 5-point scale (where 1 indicated that a specific color was not diagnostic of the object and 5 indicated that a specific color was highly diagnostic of the object). A similar method was used by Uttl and colleagues (Uttl, Graf, & Santacruz, 2006) and Bramão and colleagues (Bramão, Faísca, Petersson, & Reis, 2010; Bramão, Inácio, Faísca, Reis, & Petersson, 2011). It is possible that when a stricter method is used to determine color diagnosticity, such as the one used by Tanaka and Presnell (1999), color information appears to facilitate only the recognition of color diagnostic objects. However, when less strict criteria are used, objects not so strongly associated with a specific color might be classified as diagnostic. In fact, we observed that items classified as low color diagnostic objects by Tanaka and Presnell (1999) were considered as color diagnostic objects by Rossion and Pourtois (2004). For example, nail and fork were considered as low color diagnostic objects by Tanaka and Presnell (1999); however, Rossion and Pourtois (2004)found color diagnostic rates of 4.45 and 4.09, respectively, on their 5 point scale.

Object Semantic Category

The role of color in the recognition of objects from different semantic categories is a topic that also has been addressed in the literature. Price and Humphreys (1989) 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. Moreover, Wurm and colleagues (Wurm, Legge, Isenberg, & Luebker, 1993) showed that prototype 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. In a recent study, Laws and Hunter (2006) examined the role of color and blurring in two naming experiments across natural and artifact categories. When the objects were presented in a non blurred format the authors report no color advantage in the naming accuracy for both categories, although the error rates were very low. However, interestingly when the objects were presented in a blurred format, a color advantage for the naming accuracy was found for objects belonging to the natural categories, but not for objects belonging to artifact categories. The authors argue that the blurring of the images may increase the level of visual crowding and that color might be therefore helpful segmenting the shape components of the natural objects.

Additionally, 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, Faísca, Forkstam, Reis, & Petersson, 2010; Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006).

Object Recognition Task

The studies reviewed here mostly used naming, object-name verification, and semantic classification (natural versus artifact) tasks to evaluate the role of color in object recognition. Different object recognition tasks impose different cognitive demands (Humphreys, Price, & Riddoch, 1999). To name an object, subjects must activate the semantic representation and the name of a specific object; in contrast, to perform a semantic classification task, they only need to activate the semantic representation. A dissociation of the color effects in these two tasks might indicate the visual recognition stage at which color information affects object recognition process. To match an object with a previous presented name, subjects needed to activated semantic and object name representations. Biederman and Ju (1988) did not find any advantage of color in semantic verification tasks. Nevertheless, they found a small but significant advantage of color in one of their object naming experiments (unmasked condition); however, this advantage was not replicated in the masked condition. Davidoff and colleagues also failed to find any color effect on semantic classification but reported an advantage of color in object naming (Davidoff & Ostergaard, 1988; Ostergaard & Davidoff, 1985).

The finding that color information improves object naming to a greater degree than semantic categorization led some researchers to propose that color effects are reserved for latter stages of visual processing (i.e., after semantic access has occurred) and thus provide an associative link between the representations of object shape and object name (Davidoff, 1991; Davidoff & Ostergaard, 1988; Tanaka, Weiskopf, & Williams, 2001). However, a number of recent investigations have not replicated these findings and have instead reported a recognition advantage related to color information, both in naming and semantic verification tasks for objects (e.g., Therriault, Yaxley, & Zwaan, 2009) as well as visual scenes (e.g., Oliva & Schyns, 2000). These findings suggest that the role of color is not restricted to the access of the name representations. In line with this hypothesis, several studies have reported color effects in the early stages of visual processing (Gegenfurtner & Rieger, 2000; Wurm, Legge, Isenberg, & Luebker, 1993). For example, Wurm and colleagues (Wurm, Legge, Isenberg, & Luebker, 1993) found evidence for a low-level sensory contribution, as color improved object identification irrespective of color diagnosticity. Others have argued that color is represented at a perceptual level in a structural representation system (Price & Humphreys, 1989) and/or at a semantic level where stored conceptual knowledge of prototypical object color provides an associative link between a representation of object shape and the object name (Davidoff, Walsh, & Wagemans, 1997). In support of this idea, there is evidence suggesting that stored knowledge of object color also plays a role in object identification (Joseph, 1997; Joseph & Proffitt, 1996; Mapelli & Behrmann, 1997).

Stimulus Type

Recently, Uttl and colleagues (Uttl, Graf, & Santacruz, 2006) suggested that a line-drawing of an object is typically viewed as a representative of an object class – a type – while photographs are viewed as an individual object – a token. The recognition of types and tokens may recruit different perceptual and semantic processes and for that reason color information might make a different contribution when recognizing a line-drawing rather than a photograph. Most of the studies that evaluate the role of color in object recognition have compared black-and-white and color line-drawings (e.g., Vernon & Lloyd-Jones, 2003) or black-and-white and color photographs (e.g., Lloyd-Jones & Nakabayashi, 2009).

Only three studies explored both line-drawings and photographs of the same object in investigating the role of color information in object recognition. In these studies the impact of color information was evaluated using color and black-and-white photographs and color and black-and-white line-drawings similar to the photographs. Two studies reported a similar color advantage for both stimulus type (Bramão, Inácio, Faísca, Reis, & Petersson, 2011; Price & Humphreys, 1989). The third study explored the effect of color, using both line-drawings and photographs, by comparing the performance of illiterate and literate elderly subjects in a naming task. The authors showed that whereas the illiterate subjects benefitted from color information in line-drawings and in photographs, the literate subjects only benefitted from color information in line-drawings and not in photographs (Reis, Faísca, Ingvar, & Petersson, 2006).

In a recent study, Adlington, Laws and Gale (2009b) investigated the naming performance of a group of patients with Alzheimer’s disease (AD) and elderly controls using color photographs, monochromatic photographs and line-drawings derived from the photographs. The authors showed that the naming accuracy of the control group improved with the addition of surface detail (photographs) and with the addition of color. However, the naming accuracy of the AD patients did not improve with the addition of color or surface details.

Surface Details

Color is usually displayed together with other surface properties, for example texture and shadow. Most of the studies in this review used color object images that displayed color together with other surface information, making it difficult to distinguish the color effect from the effect of other surface details. None of the studies reviewed here investigated the color effect in images with and without other surface properties. However, four independent experiments reported a color effect using images without other surface properties besides color (Joseph, 1997; Moore & Price, 1999a; Vernon & Lloyd-Jones, 2003), suggesting that color alone is a property that improves object recognition.

Snodgrass and Vanderwart Set (1980)

The Snodgrass and Vanderwart set (1980) of images is one of the most used set of objects in cognitive experimental research. Snodgrass and Vanderwart (1980) presented a normative picture set of 260 line-drawings of common objects from different semantic categories, together with normative data for familiarity, visual complexity and name agreement for the English language. Subsequently, this set of objects have been standardized in different languages, including French (Alario & Ferrand, 1999; Bonin, Peereman, Malardier, Méot, & Chalard, 2003), Italian (Dell'Acqua, Lotto, & Job, 2000), Spanish (Cuetos, Ellis, & Alvarez, 1999; Sanfeliu & Fernandez, 1996) and Portuguese (Ventura, 2003), among others. More recently, Rossion and Pourtois (2004) modified the 260 line-drawings from the set of Snodgrass and Vanderwart by adding texture and shadow details. Because the Snodgrass and Vanderwart set is one of the most used set of objects in cognitive science research, it might be of interest to explore the color effects using this specific set of objects compared to a set of different objects.

7.2 Methods

Study Selection

Studies included in the meta-analysis were identified and select by searching the PubMed and PsycINFO databases, using the search terms “surface detail”, “surface information”, “colo(u)r diagnosticity”, “colo(u)r AND object recognition”, and “colo(u)r AND object identification” during March and April 2010. This procedure identified 93 articles. The title and abstract of the initial set of articles were screened for potential inclusion, leaving 34 studies that met at least some of the inclusion criteria. For inclusion in the meta-analysis, a study had to meet the following inclusion criteria: 1) include report response time data from object recognition tasks, 2) have presented the stimuli both in typical color and in a black and white or gray-scale version, 3) used participants between 18 and 60 years of age, 4) used participants that were healthy, and 5) contain information that allowed the computation of effect size. In general, subjects perform close to ceiling in the object recognition tasks, and for that reason we did not consider the accuracy data in the meta-analysis. The average of the error rate for the studies included in the meta-analysis is less than 5%. Thus, studies not reporting response times (Laws & Hunter, 2006; Uttl, Graf, & Santacruz, 2006), that used visual scenes as stimuli (Gegenfurtner & Rieger, 2000; Oliva & Schyns, 2000), or only presented data from typical or atypical colored objects (Joseph & Proffitt, 1996; Naor-Raz & Tarr, 2003) were excluded from the meta-analysis. Also, studies presenting data from elderly subjects (Boucart, Despretz, Hladiuk, & Desmettre, 2008; Reis, Faísca, Ingvar, & Petersson, 2006), from brain lesioned (Mapelli & Behrmann, 1997) or non-normal vision individuals (Boucart, Despretz, Hladiuk, & Desmettre, 2008) were not included in the meta-analysis. One study was excluded because it did not provide sufficient information to compute the effect size (Nagai & Yokosawa, 2003).

From the initial pool of 34 studies, only 10 met all of the inclusion criteria. Thus, some of the studies included in the literature review above were not included in the meta-analysis. Further, the bibliographies from the ten papers identified as outlined were inspected, and eight additional relevant references were identified. Selected studies were restricted to those appearing in English language journals, with the exception of one non-published study (Faísca et al., 2004). The non-published study was conducted in our lab and intended to establish normative data for the Portuguese population related to naming response times for a set of 70 object representations. In this study, the objects were presented both as line-drawings and as photographs. The line-drawings, selected from the original Snodgrass and Vanderwart (1980) set, were presented as contours (without surface details) and in a gray-scale and colored version selected from the set generated by Rossion and Pourtois (2004). The photographs were also presented in a color and in a black and white version that matched as far as possible in terms of color, size, shape and orientation to the line-drawings.

The 18 resultant articles and the non-published study yielded 35 independent experiments where the object recognition performance, evaluated in terms of response time, was tested in a typical colored and in a black and white object version (see **Figure 7.1**).

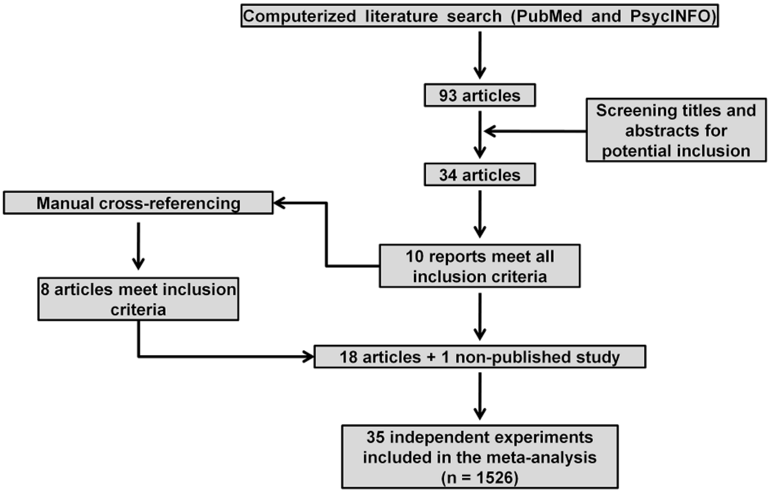

Figure 7.1. Flow chart of studies considered and finally selected for inclusion in the meta-analysis.

Data Extraction

For each study, we extracted information about the stimulus characteristics: color diagnosticity status (diagnostic *versus* non-diagnostic color), semantic category (natural object *versus* artifact), stimulus type (line-drawings *versus* photographs), surface details (present *versus* absent) and stimulus set (Snodgrass and Vanderwart (1980) set *versus* other sets). We also identified for each study the object recognition task used. Finally, for each study we checked whether low level visual properties of the images (for instance, luminance and contrast) were controlled between the black-and-white and the color conditions (see **Table 7.1**). This information is important for assessing the moderator effect on the role of color in object recognition of the following variables: (1) object color diagnosticity, (2) object semantic category, (3) type of recognition task, (4) stimuli type (line-drawing *versus* photographs), (5) presence of stimuli surface details, and (6) if the experimental stimuli belong to the Snodgrass and Vanderwart (1980) set.

Color diagnosticity

None of the studies selected in the meta-analysis tested the effects of color exclusively for non-diagnostic objects. To maximize the likelihood of meeting the methodological assumption that effect size estimates taken from individual studies are independent of each other, whenever a study presented both the information for color and non-color diagnostic objects, we only selected the information about the non-color diagnostic objects. Thus, the moderator effect of color diagnosticity was assessed by comparing the effect size estimated from studies that tested the color effect only in color diagnostic objects with the effect size from studies that tested color effects on both color and non-color diagnostic objects but using only the information about the non-color diagnostic objects.

Object Semantic Category

Only one of the studies selected to be part of the meta-analysis tested the color effects exclusively in artifacts (Brodie, Wallace, & Sharrat, 1991). To test the semantic category influence on the color effect, while maximizing the likelihood of meeting the methodological assumption that effect size values came from independent studies, we used a similar procedure to the one adopted to evaluate the color diagnosticity effects: whenever a study presented both the information for natural objects and artifacts, we only selected the information about the objects belonging to the artifact category. Consequently, the effect of the semantic category was assessed by comparing the effect size estimated from studies that tested the color effect only in natural objects with the effect size from studies that tested both artifacts and natural objects but using only the information about the artifacts.

Object Recognition Task: Naming versus Semantic Classification Task versus Verification Task

Only one experiment included in this meta-analysis tested the color effects in object recognition using exclusively a semantic classification task (where subjects had to decide if a present object was from a natural or an artifact semantic category; Price & Humphreys, 1989). Five experiments tested the color effects using exclusively verification tasks (where subjects had to match a previous presented name/object with a object/name; Biederman & Ju, 1988; Bramão, Faísca, Petersson, & Reis, 2010; Tanaka & Presnell, 1999). To test the moderator effect of the object recognition task, while assuming that the effect size values came from independent studies, we employed a similar procedure to the one adopted to evaluate the color diagnosticity effects: whenever a study presented both the information for semantic classification task or verification task together with other visual tasks, we only selected the information about the semantic classification or about the verification task. As a result, the moderator role of the recognition task was evaluated by contrasting the effect size estimated from studies that assessed color effects in naming tasks with the effect size from studies that used semantic classification tasks and from studies that used verification tasks (object-name or name-object verifications).

Stimulus Type

The effect of the stimulus type was assessed by comparing the effect size estimated from studies that compared color and black-and-white photographs with effect size from studies that compared color and black-and-white line-drawings.

Surface Details

The effect of surface details was evaluated by comparing the effect size from studies that used stimuli with surface details both in the colored and in the black and white version of the stimuli with the effect size estimated from studies that used colored and black-and-white objects without surface details. The surface details considered in the meta-analysis were texture and shadow.

Snodgrass and Vanderwart Set (1980)

The object set effect was evaluated by comparing the effect size estimated from studies that used stimuli from the Snodgrass and Vanderwart (1980) set or its colored version from Rossion and Pourtois (2004) set with the effect size estimated from studies that used another object set. The studies using photographs were not included in this comparison.

Effect Size Estimates

Data were analyzed with the Comprehensive Meta-Analysis software v.2.2. For each color versus black and white comparison, we calculated Cohen’s *d* to estimate the magnitude of the color effect on the response time data. When means and standard deviation were not provided, *d* values were estimated from reported t or

F statistics. A positive d value indicates a color effect. By convention, an effect size of ±0.2 is considered to be a small effect, a value of ±0.4 is a moderate effect and a value of ±0.6 or greater is considered a relatively large effect. For each meta-analysis, we calculated the 95% confidence interval (CI), statistical significance (*p*), within-group heterogeneity (Q_{within}), and the percentage of variation across studies due to heterogeneity rather than sampling error (I^2). For additional clarification of differences between effect size estimates, we proceeded with a subgroup analysis to test the moderator variable effects, with mixed-effects between-group heterogeneity ($Q_{between}$). Studies varied according to sample size (range 8–180); this creates a risk that a small, outlying sample will exert disproportionate influence over the mean effect size. To minimize this risk, we weighted the effect size estimates by sample size (Rosenthal, 1991). When individual studies included multiple independent experiments, separate effect sizes were calculated for each experiment. When studies presented information sufficient to derive more than one effect size estimate for an individual experiment, effect size estimates were in some cases (for example, in the overall analysis) aggregated using the arithmetic mean. This aggregation prior to meta-analytic integration is necessary to avoid the over representation of multi-experiment studies in the overall analyses (Rosenthal, 1991).

7.3 Results

Overall

An overall effect size was calculated that incorporates all 35 effect sizes, comprising a total of 1535 subjects. The summarized results indicate a moderate significant color information effect on object recognition ($d = 0.28$, 95% CI = 0.19 – 0.38, $p < 0.001$). Moreover, the heterogeneity test was significant ($Q_{within} = 88.87$, $p < 0.001$, $I^2 = 61.74\%$), suggesting that more than two-thirds of the observed variance was not accounted for by sampling error. This finding implies that further meta-analytic subdivision of the overall sample was warranted. A systematic analysis of theoretically meaningful (selected a priori) moderator variables was therefore conducted on six subsets of the overall pool of studies. The results of the separated meta-analysis are given in **Figure 7.2** and **Table 7.2**.

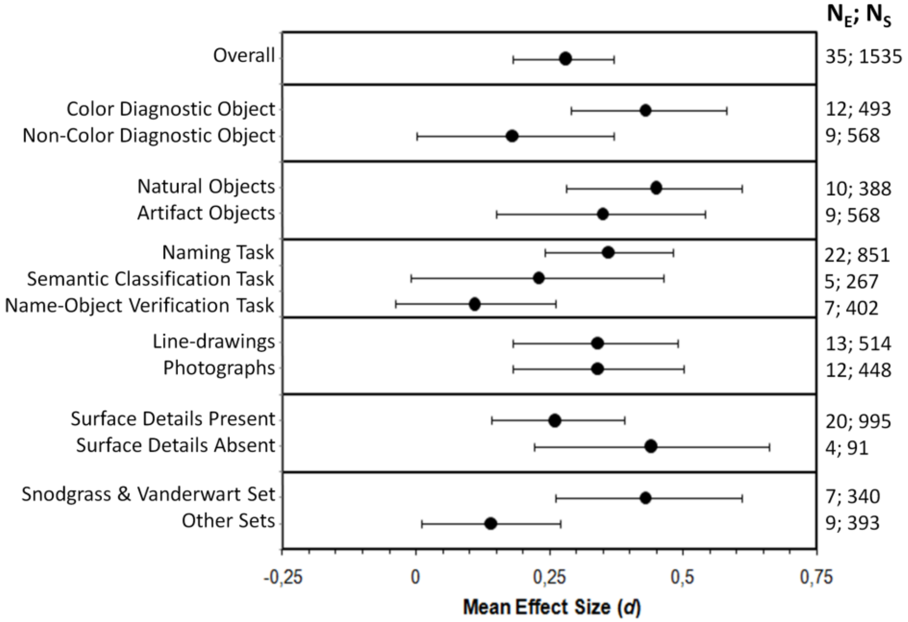

Figure 7.2. Mean effect size (*d*) and 95% confidence intervals for the 13 meta-analysis conducted. The moderator variables tested in specific meta-analytic comparison are labeled on the left side. Labels to the right side of the figure indicate the number of independent effect sizes (experiments) which contributed to each meta-analysis (N_E), and the number of subjects these effect sizes were based upon (N_s).

Color Diagnosticity

To assess the effect of color diagnosticity, we compared studies where the color effect was evaluated using color diagnostic objects with studies using non-color diagnostic objects. This comparison was significant ($Q_{between}$ = 4.28, *p* = 0.04), with greater effects observed in studies where the color effect was assessed using color diagnostic objects. In fact, studies using non-color diagnostic objects showed a marginally significant color effect (*d* = 0.18, *p* = 0.06), whereas studies using color diagnostic objects showed a moderate color effect (*d* = 0.43, *p* < 0.001).

Semantic Category

The color effect in studies that used objects from natural categories was compared with the effect from studies that used artifact categories. We did not find any difference in the color effect estimated from these two types of studies ($Q_{between}$ = 0.59, *p* = 0.44). Studies that used natural objects and artifacts showed a similar color advantage effect (natural objects: *d* = 0.45, *p* < 0.001; and artifacts: *d* = 0.36, *p* < 0.001).

Object Recognition Task

To examine the moderator effect of the recognition task, we compared studies that used naming tasks with those that used semantic classification and verification tasks. The comparison was significant ($Q_{between}$ = 6.46, *p* = 0.04); studies that used naming tasks showed a moderate color effect (*d* = 0.36, *p* < 0.001), while studies that used verification tasks did not show a significant color effect (*d* = 0.11, *p* = 0.15). Studies that used semantic classification tasks showed a marginally significant color effect (*d* = 0.23, *p* = 0.06).

Stimuli Type

The color effect in studies that used line-drawings was compared with studies that used photographs. We did not find a significant difference between the two types of studies ($Q_{between}$ = 0.001, *p* = 0.97); both showed a moderate color effect (line-drawings: *d* = 0.35, *p* < 0.001; photographs: *d* = 0.34, *p* < 0.001).

Surface Details

The estimated color effect from studies that used colored stimuli together with other surface details, such as shadow and texture, was compared with the estimated color effect from studies that used stimuli without surface details. The comparison did not show significant results ($Q_{between} = 2.06$, $p = 0.15$), although both types of studies showed significant effect sizes (surface details present: $d = 0.26$, $p < 0.001$; surface details absent: $d = 0.44$, $p < 0.001$).

Snodgrass and Vanderwart Set (1980)

To evaluate the moderator effect of using the Snodgrass and Vanderwart set (1980), we estimated an effect size of color information from studies that used these stimuli, and we compared it to the effect size of color from studies that used other object sets. Our results show that the color advantage is greater in studies that used the Snodgrass and Vanderwart set compared to studies that used other object sets ($Q_{between} = 6.83$, $p = 0.01$). Although both types of studies were associated with significant effect sizes, a larger effect for those studies using the Snodgrass and Vanderwart set ($d = 0.43$, $p < 0.001$) was observed compared to studies that used other object sets ($d = 0.14$, $p < 0.001$).

7.4 Discussion

In this meta-analytic review of 35 independent experiments, we intended to clarify the role of color information in object recognition. The overall meta-analysis unambiguously revealed that, in contrast to occasional declarations to the contrary (Biederman & Ju, 1988), color information improves object recognition. This result suggests that object recognition theories should consider the role of color information and elaborate its role in object recognition. Moreover, if we consider the evolution of the human species, then color vision most likely developed for specialized uses, including detecting ripe fruit amongst foliage (Gegenfurtner, 2003; Surridge, Osorio, & Mundy, 2003). Taking such considerations together with the fact that color plays a prominent part in our subjective experience of the visual world, it would make sense to include color processing, and its consequences, as an integral part of models of object recognition (Tanaka, Weiskopf, & Williams, 2001).

This meta-analysis also shows that the contribution of color information to object recognition depends on object properties and task conditions. In particular, the results show that color information participates in the recognition of color diagnostic objects but less so in the recognition of the non-color diagnostic objects. This result is not consistent with the color diagnosticity hypothesis formulated by Tanaka and Presnell (1999; see also Nagai & Yokosawa, 2003), that proposed that color information only improves the recognition of high color diagnostic objects. In the literature review, we also found a large body of evidence showing a color advantage both for color and non-color diagnostic objects (Biederman & Ju, 1988; Bramão, Faísca, Petersson, & Reis, 2010; Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006; Wurm, Legge, Isenberg, & Luebker, 1993). Still, the studies that report a color advantage in the non-color diagnostic objects recognition always showed a greater effect for color in color diagnostic object recognition (e.g., Rossion & Pourtois, 2004). This observation is congruent with our meta-analytic result: a strong color effect for color diagnostic objects and a small color effect for non-color diagnostic objects. Moreover, in a recent study (Bramão, Inácio, Faísca, Reis, & Petersson, 2011), we observed that color information effects are restricted to the early stages of the visual processing for the non-color diagnostic objects. In that sense, the failure to find strong color effects for non-color diagnostic objects could be related to the nature of the recognition tasks. It might be that the color effect in non-color diagnostic object recognition is only evident when the recognition task is perceptually demanding. It is also important to note that the Q statistic indicates that the effect size estimate for these two groups of studies are not homogenous reflecting high variability between studies (color diagnostic objects: $Q_{within} = 24.12$, $p = 0.01$; non-color diagnostic objects: $Q_{within} = 24.93$, $p < 0.001$). However, the limited number of studies did not allow us to further investigate what other variables could account for this heterogeneity.

Several methods have been used to classify the color diagnosticity of a particular object. Research investigating the contribution of color information to object recognition would benefit from a standardization of the method to measure color diagnosticity. Tanaka and Presnell (1999) assessed color diagnosticity using two criteria: feature listing and typicality judgments. In the feature-listing task, the subjects listed perceptual features associated with an object. In the typicality task, the subjects were asked to indicate the color that was most typical of an object. An object was rated as high in color diagnosticity only if a specific color was consistently mentioned first in the feature list and was rated as the typical color. This approach might be too strict and might prevent objects that are moderately or even strongly associated with a specific color from being classified as color diagnostic objects. Moreover, the feature listing task assesses which properties are more typical and distinct for an object and not if this object is highly associated with a particular color or not. Using a much more straightforward task, Rossion and Pourtois (2004) evaluated the color diagnosticity of the objects with a 5-point rating scale. They present each colorized object to a group of subjects and asked them to rate the object according to the following instruction: “give a score between 1 (the color of the object depicted is not diagnostic at all, i.e. this object could be in any other color equally well) and 5 (the color depicted is highly diagnostic of the object, i.e. the object appears only with that color in real life)”. We propose that such a method is more indicated to assess if a particular object is or not associated with a specific color. Moreover, we also think that one important aspect in this context is to ask subjects to not classify the object image itself but, instead, to classify the object concept as being associated or not with a specific color. This approach might help to avoid results being dependent on a particular set of images, making studies more homogeneous and thus more comparable.

An important consideration is that most of the studies that explored the role of color diagnosticity in object recognition classify the objects as being either color diagnostic or non-color diagnostic (see, for an exception, Rossion & Pourtois, 2004).

We believe that color diagnosticity status is probably better described as a continuous variable, with high color diagnostic objects lying on one end of the continuum, the non-color diagnostic objects on the other end, and the objects with moderate color associations lying somewhere in between.

The meta-analytic results also showed a similar color advantage effect for studies that used natural objects and artifacts. This result was expected and is consistent with the large body of literature (Bramão, Faísca, Forkstam, Reis, & Petersson, 2010; Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). However, it is important to note that the Q statistic indicates that the effect size estimates for these two groups of studies are non-homogenous, reflecting high variability (natural objects: $Q_{within} = 19.67$, $p = 0.02$; artifacts: $Q_{within} = 16.63$, $p = 0.03$). It would be interesting to determine what other variables are contributing to the high variability, for example, to cross the semantic category variable with the color diagnostic variable. However, the limited number of studies available prevented us from pursuing such analyses.

Another interesting result that was revealed in the meta-analysis is the fact that color information contributes to object recognition mainly in studies that used naming tasks but less so in studies that used semantic classification tasks. Surprisingly, the studies that used verification tasks did not show a significant color effect. These tasks also require semantic and name activation similar to the naming task. In the literature review, we found a robust body of evidence showing that color information improves object recognition in object and scene verification tasks; however, the meta-analysis did not replicate this finding. One possible explanation for the discrepancy could be related with the color diagnosticity factor. In fact, on close examination, out of the seven studies that employed a verification task, only two experiments used only color diagnostic objects (Joseph, 1997; Therriault, Yaxley, & Zwaan, 2009). Two other used both color and non-color diagnostic objects (Biederman & Ju, 1988), and in the other three experiments we only considered the non-color diagnostic objects results (to guarantee that effect size values came from independent studies; Bramão, Faísca, Petersson, & Reis, 2010; Tanaka & Presnell, 1999). It is also relevant to note that the effect sizes in studies that used naming and semantic classification tasks are non-homogeneous, which suggests that other sources are causing the between-study variability (naming task: $Q_{within} = 46.31$, $p < 0.001$; semantic classification task: $Q_{within} = 11.06$, $p = 0.03$).

The fully understating of which object recognition tasks might benefit or not with color information is an important insight to understand the level of processing at which color information improves object recognition. In the literature review, we also found evidence that color information improves object naming to a greater degree than semantic classifications (Biederman & Ju, 1988; Davidoff & Ostergaard, 1988). In fact, Davidoff (1991) proposed a model of object recognition where color information is considered to participate in object recognition only in the later stages of the visual processing, after the structural description of the object is achieved. In this model, the pictorial input is analyzed by a boundary feature contour system. This information is then temporary stored and activates the object structural description. The object structural description is spatially defined by shape and size information, but not by color. Then the associated stored knowledge for that particular object is activated. Davidoff (1991) considered two basic forms of stored knowledge: the *hasa* knowledge concerning sensory information and the *isa* knowledge concerning information about the function of the object. Object color, according to this model, is specifically part of the associated *hasa* properties. So, the color effects in object recognition are considered to take place after the initial visual representation. In concordance with the prediction that color information is not available in the structural descriptions, Davidoff and Ostergaard (1988) found that the introduction of color did not improve performance in a size comparison task.

The absence of color at the stored structural description was first disputed by Price and Humphreys (1989). The authors showed that color is required at the structural description stage to disambiguate objects from categories that are structurally similar and proposed that the characteristic color of an object is represented in its structural representation. The authors argued that there are separated representations for color and shape, but that these representations are richly interconnected. Appropriated color objects activate color representations that in turn activate associated shape representations (Humphreys, Goodale, Jakobson, & Servos, 1994; Price & Humphreys, 1989). Actually, it has been reported that when the correlation between color and shape is high, as it is in color diagnostic objects, the presence of color aids recognition at a greater degree than thus when the correlation between shape and color is low, as it is in the case of non-color diagnostic objects (e.g., Rossion & Pourtois, 2004). In a recent study, we also showed that the role of color information in object recognition is dependent of the color diagnosticity status of the objects (Bramão, Inácio, Faísca, Reis, & Petersson, 2011). For the recognition of the color diagnostic objects, color information was especially important at the semantic representation level, whereas for non-color diagnostic objects, color information improved object recognition only at the early stages of the visual processing. These results may suggest that color improves object recognition in the early stages of the visual processing for all objects. However, since non-color diagnostic objects are not strongly associated with a color, no further color advantage is expected at the higher processing levels.

Moreover, based on the review of the literature, it seems plausible that color information might contribute in more ways to object recognition than only to provide a link between the object shape and object name representations and to facilitate semantic access for color diagnostic objects. The studies included in our meta-analysis mostly investigated naming, object verification and semantic classification tasks and this made it impossible to test whether color also has a role in the early processing stages of object recognition. However, there is evidence suggesting that this might actually be the case (Davidoff, Walsh, & Wagemans, 1997; Gegenfurtner & Rieger, 2000; Wurm, Legge, Isenberg, & Luebker, 1993). For example, Gegenfurtner and Rieger (Gegenfurtner & Rieger, 2000) tested the role of color vision in the recognition of briefly presented images of natural scenes using a delayed match-to-sample task. The results showed a clear (and rapid) effect of color on the recognition of natural images in at least two ways: at an early stage, where color contributes with an additional cue for image segmentation; and at a later stage, where color serves as a cue for memory retrieval. Further research is needed to clarify the role of color and the processing stages where color information improves (or hinders) object recognition.

Additional moderator variables related to the effects of stimulus characteristics (stimulus type and surface detail) were explored in the meta-analysis. We observed color effects independent of these characteristics. Thus, it seems that color information does not play a different role in the recognition of a type (line-drawings) and a token (photographs) and that color alone (i.e., without other surface details) unambiguously improves object recognition, which is consistent with the findings of the literature review (Bramão, Inácio, Faísca, Reis, & Petersson, 2011; Joseph, 1997; Moore & Price, 1999a; Price & Humphreys, 1989; Reis, Faísca, Ingvar, & Petersson, 2006; Vernon & Lloyd-Jones, 2003). The homogeneity measures (Q and I^2) indicated that the effect size for these groups of studies were non-homogenous, suggesting that other variables contribute to the high variability between studies. However, the limited number of studies does not allow us to further explore other potential sources of variability.

Interestingly, we found a superior color advantage for studies that used the Snodgrass and Vanderwart set (1980) or its colored version (from Rossion and Pourtois 2004). This advantage could be due to the set itself and the way the objects are drawn or painted. Other differences between the Snodgrass and Vanderwart set and other object sets have been reported in the literature. For example, Laws and colleagues (2007) point out that Snodgrass and Vanderwart set produces normal subjects to perform near to ceiling which can exacerbate the naming effect sizes when the naming performance of the clinical populations is compared with the naming performance of the normal controls groups (Laws, Adlington, Gale, Moreno-Martínez, & Sartori, 2007). To solve this problem the authors construct a new set of pictures were pictures of not so familiar objects are also included (Adlington, Laws, & Gale, 2009a). Once more, the homogeneity measures (Q and I^2) indicate that the effect size for the studies that used the Snodgrass and Vanderwart set were not homogenous.

In summary, the literature review and the meta-analysis both suggest that color information contributes to object recognition specially when objects are strongly associated with a color, but also when object are not so strongly associated with a particular color. Color information also improves, to the same degree, the recognition of natural objects and artifacts, as well as the recognition of tokens (photographs) and types (line-drawings). Thus, the color advantage effect seems to be independent of other surface details, including shadows and texture. Finally, in almost all the subsets of the included studies, the effect size estimates are heterogeneous, with the exception of the following: studies that used images without surface details, and studies not using the Snodgrass and Vanderwart set (1980). We suggest that it is important to explore the sources of heterogeneity in future research.

Acknowledgements

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Table 7.1. Characteristics of the studies included in the meta-analysis.

Study	*d*	N	Color Diagnosticity	Semantic Category	Task	Color Stimuli	B&W Stimuli	Color Details	B&W Details	S&V	Visual Properties
Biederman and Ju (1988) Exp. 1	-0.18	30	ND/DI	AO/NA	naming	PH	LD	yes	no	no	not reported
Biederman and Ju (1988) Exp. 2	0.18	30	ND/DI	AO/NA	naming	PH	LD	yes	no	no	not reported
Biederman and Ju (1988) Exp. 3	0.18	30	ND/DI	AO/NA	naming	PH	LD	yes	no	no	not reported
Biederman and Ju (1988) Exp. 4	-0.10	96	ND/DI	AO/NA	VT	PH	LD	yes	no	no	not reported
Biederman and Ju (1988) Exp. 5	0.10	96	ND/DI	AO/NA	VT	PH	LD	yes	no	no	not reported
Bramão et al. (2010)	0.55	20	ND/DI	AO	naming	LD	LD	yes	yes	yes	controlled
Bramão et al. (2010)	0.12	28	ND	AO	VT	PH	PH	yes	yes	no	controlled
Bramão et al. (2011)	-0.02	144	ND	AO/NA	SCT	PH/LD	PH/LD	yes	yes	no	controlled
Brodie et al. (1991) Exp. 3	0.00	18	ND/DI	AO	naming	PH	PH	yes	yes	no	controlled
Brodie et al. (1991) Exp. 4	0.55	15	ND/DI	AO	OVT	PH	PH	yes	yes	no	controlled
Chao and Martin (1999)	-0.11	12	---	---	naming	---	---	---	---	---	not reported
Davidoff and Ostergaard (1988) Exp. 1	0.32	32	ND/DI	AO/NA	SCT	LD	LD	yes	no	yes	controlled
Davidoff and Ostergaard (1988) Exp. 2	0.83	16	ND/DI	AO/NA	SCT	LD	LD	yes	no	yes	controlled
Faísca et al. (2004)	0.08	60	ND	AO	naming	PH/LD	PH/LD	yes	yes	yes/no	controlled
Gale et al. (2006) Exp. 4	0.39	32	ND/DI	AO	naming	LD	LD	yes	no	yes	controlled
Hocking and Price (2008)	0.33	15	ND/DI	AO/NA	naming	PH	PH	yes	yes	no	not reported
Humphreys et al. (1994) Exp 2	0.51	37	ND	AO	naming	PH	PH	yes	yes	no	controlled
Humphreys et al. (1994) Exp 3	1.64	30	DI	NO	naming	PH	PH	yes	yes	no	controlled
Joseph (1997)	0.77	23	DI	NO	VT	LD	LD	no	no	no	not reported

Lloyde-Jones and Nakabayashi (2009)	0.59	21	DI	AO/NA	naming	PH	PH	yes	yes	no	controlled
Moore and Price (1999a) Exp. 1	0.24	8	ND	AO	naming	LD	LD	no	no	no	not reported
Oostergard and Davidoff (1985) Exp. 1	0.65	45	DI	NO	naming	PH	PH	yes	yes	no	controlled
Oostergard and Davidoff (1985) Exp. 2	0.36	75	DI	NO	naming	PH	PH	yes	yes	no	controlled
Oostergard and Davidoff (1985) Exp. 3	0.38	32	DI	NO	naming	PH	PH	yes	yes	no	controlled
Price and Humphreys (1989) Exp 1	0.13	50	DI	NO	SCT	PH/LD	PH/LD	yes/no	yes/no	no	controlled
Price and Humphreys (1989) Exp 2	0.31	25	DI	NO	SCT	PH/LD	PH/LD	yes/no	yes/no	no	controlled
Rayn et al. (2003) Exp. 2	0.05	32	ND/DI	AO/NA	naming	LD	LD	yes	yes	no	not reported
Rossion and Pourtois (2004)	0.71	180	ND	AO	naming	LD	LD	yes	yes	yes	controlled
Tanaka and Presnell (1999) Exp. 2	0.03	45	ND	AO/NA	VT	LD	LD	yes	yes	no	controlled
Tanaka and Presnell (1999) Exp. 3	0.10	36	ND	AO/NA	naming	LD	LD	yes	yes	no	controlled
Tanaka and Presnell (1999) Exp. 4b	0.04	30	ND	AO/NA	VT	LD	LD	yes	yes	no	controlled
Therriault et al. (2009) Exp. 1	0.18	84	DI	AO/NA	VT	PH	PH	yes	yes	no	not reported
Vernon and Lloyd-Jones (2003) Exp. 1a	0.40	30	DI	NO	naming	LD	LD	no	no	yes	controlled
Vernon and Lloyd-Jones (2003) Exp. 1b	0.35	30	DI	NO	naming	LD	LD	no	no	yes	controlled
Wurm et al. (1993) Exp. 2	0.41	48	DI	NO	naming	PH	PH	yes	yes	no	controlled

Effect sizes (*d*) for each study, the total number of subjects these effect sizes were based upon (N). DI – Color diagnostic objects, ND – Non-color diagnostic object. NO – Natural objects, AO – Artifacts objects. VT – verification task, OVT – object verification task, SCT – semantic classification task. LD – Line-drawings, PH – Photographs. S&V? – Did the study use the Snodgrass and Vanderwart set (1980)? Visual Properties? – Did the study control the low level visual properties?

Table 7.2. Effect Sizes and comparisons across the subgroups.

	Effect Size and 95% confidence interval							Heterogeneity				
	N_e	**N_s**	***d***	**Lower Limit**	**Upper Limit**	**Z-value**	***p* value**	**Q_{within}**	***p* value**	**I^2**	**$Q_{between}$**	***p* value**
Overall	35	1535	0.28	0.19	0.38	5.9	0.00	88.87	0.00	61.74		
Color Diagnosticity												
Color diagnostic objects	12	493	0.43	0.28	0.58	5.73	0.00	24.12	0.01	54.40		
Non-color diagnostic objects	9	568	0.18	-0.01	0.36	1.87	0.06	24.93	0.00	67.91		
											4.28	0.04
Semantic Category												
Natural Objects	10	388	0.45	0.29	0.62	5.39	0.00	19.67	0.02	54.25		
Artifacts Objects	9	398	0.35	0.16	0.55	3.54	0.00	16.63	0.03	51.89		
											0.59	0.44
Object Recognition Task												
Naming Task	22	851	0.36	0.24	0.48	5.81	0.00	46.31	0.00	54.65		
Semantic Classification Task	5	267	0.23	0.00	0.46	1.92	0.06	11.06	0.03	63.84		
Name-Object Verification Task	7	402	0.11	-0.04	0.26	1.43	0.15	12.05	0.06	50.21		
											6.46	0.04
Stimuli Type												
Line-Drawings	13	514	0.35	0.19	0.50	4.31	0.00	26.48	0.01	54.68		
Photographs	12	448	0.34	0.18	0.50	4.24	0.00	21.85	0.03	49.65		
											0.001	0.98
Surface Details												
Present Surface Details	20	995	0.26	0.13	0.38	4.08	0.00	49.06	0.00	61.27		
Absent Surface Details	4	91	0.44	0.22	0.66	3.93	0.00	2.35	0.50	0.00		
											2.06	0.15
Snodgrass and Vanderwart Set (1980)												
Snodgrass and Vanderwart (1980) Set	7	340	0.43	0.25	0.60	4.84	0.00	13.23	0.07	47.10		
Other Object Sets	9	393	0.24	0.01	0.27	2.13	0.00	11.18	0.19	28.42		
											6.83	0.01

Effect sizes (*d*), 95% confidence intervals, Z-value and significance level (*p*) for each meta-analysis, number of the independent effect sizes (studies or sub-studies) that contributed to each meta-analysis (N_e), the total number of subjects these effect sizes were based upon (N_s), within-group homogeneity of variance (Q_{within}) and significance level (*p*), percentage of the variation across studies that is due to heterogeneity (I^2), between-group homogeneity of variance ($Q_{between}$) and significance level (*p*).

Chapter 8

Summary and Discussion

8.1 Summary of the Main Findings

The role of color information during object recognition was addressed in this thesis. One of the main questions investigated here was the interaction between surface color and color knowledge information during the recognition process. While surface color refers to the visual percept generated by the color present in the object image (e.g., the color red in a picture of a red strawberry), color knowledge uses semantic information about the prototypical color of an object (e.g., the knowledge that strawberries are typically red). The Shape + Surface model proposes that object recognition is achieved by a combination of the bottom-up influences of surface color information and the top-down influences of color knowledge information (Tanaka, Weiskopf, & Williams, 2001). However, the proposed model does not clarify which of these two sources of color information is the most relevant during object recognition processes. In the first two studies (chapters 2 and 3), we presented data that clarifies the interaction between surface color and color knowledge information and identifies the system with the greatest input during object recognition.

In chapter 2, a name-object verification task was used to evaluate the effect of color knowledge on object recognition. Subjects were asked to verify whether a previously presented name matched an object that could be similar or dissimilar in shape and color information. The objects were presented in three different formats: typical color, black and white, and atypical color. We predicted that, if color knowledge information contributes to the recognition process, subjects will take longer to respond in non-matching trials whenever the color knowledge information activated by the name and object are the same, not only when the objects were presented in their typical color but also when black-and-white and atypical color versions were used. Our results showed a strong effect of both shape and color information in typical color presentations: subjects were slower when the name and the object activated similar shape and color information. However, when black-and-white and atypical color versions were presented, the color similarity effect disappeared, leaving only the shape similarity effect. This result suggests that the effect of color knowledge information strongly depends on the presence of the appropriate surface color information. Moreover, it indicates that surface color plays a more prominent role during object recognition processes.

In chapter 3, ERPs (Event-Related Potentials) were used to further explore the interaction of these two sources of color in object recognition. The use of the ERP technique permitted us to evaluate when surface color and the color knowledge information are recruited during object recognition. ERPs were recorded while subjects performed two color verification tasks: a surface color and color knowledge. The perceptual color of the objects was manipulated to create a surface color interference/help in the color knowledge verification task and color knowledge interference/help in the surface color verification task. We observed a strong effect of surface color information during the color knowledge verification task, whereas no effect of the color knowledge was observed during the surface verification task. In the color knowledge verification task, subjects more quickly responded that the typical color of a strawberry was red when the image of the strawberry was colored red when compared to when it was colored gray. In the same way, subjects more slowly answered that the typical color of a mouse was not red when the image of the mouse was colored red compared to when it was colored gray. The ERP results from this task showed surface color effects in the temporal windows of the N350 and of the late positive complex (LPC) components. While the color effect found in the N350 temporal window indicates that surface color is involved in the selection of an object description form to be matched with the perceptual input, the color effect found in the LPC component suggests that color activates semantic and associative knowledge related to the presented objects. On the other hand, no effects of color knowledge were found in either the behavioral or ERP results of the surface verification task. Subjects verified with equal ease that a red strawberry and a red mouse were colored in red and that a gray strawberry and a gray mouse were not colored in red. The outcomes from this study clearly corroborate the idea that surface color information represents a more prominent input during the recognition process. Taken together, the results of these studies show that the activation of color knowledge associated with specific objects is somewhat dependent on the presence of the appropriate surface color information input, suggesting that surface color plays a more prominent role than color knowledge information during object recognition.

Another question explored in this thesis was the effect of the color diagnosticity level of specific objects on the color effects observed during object recognition. At the present moment, there is no agreement in the literature concerning the effect of color during recognition of color and non-color diagnostic objects. Although some studies report that color information only improves the recognition of color diagnostic objects (e.g., Tanaka & Presnell, 1999), others report that color information improves recognition of both color and non-color diagnostic objects (e.g., Uttl, Graf, & Santacruz, 2006). To clarify this question, we investigated the level of the visual process at which color information improves the recognition of these two types of objects (chapters 4 and 5). In these studies, recognition of color and non-color diagnostic objects was compared using color and black-and-white versions. Chapter 4 showed that, during the recognition of non-color diagnostic objects, the role of color was restricted to recognition tasks that required high visual perceptual demanding. During recognition of color diagnostic objects, however, color was found to play a role in tasks that required high semantic processing. In chapter 5, we further explored this question using ERPs. Independent of the color diagnosticity status, a color effect was found early (~100 ms) after stimulus onset, suggesting that color aids image segmentation, thus lowering the visual demand of early visual recognition stages. For color diagnostic objects, we found color effects occurred later (~350 ms) after stimulus onset. The color effects found in these later temporal windows of the ERP components indicate that color is involved in the later stages of the recognition process during recognition of color diagnostic objects. Together, these results indicate 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, during the recognition of color diagnostic objects, color information also participates in the later stages of the visual processing.

In chapter 6, brain responses related to color information were measured with functional magnetic resonance imaging (FMRI) during a covert naming task. The aim of this study was to clarify whether the neural pathways concerning color processing are the same for natural and artifacts objects. Different roles of color information have been proposed for these two categories of objects (Price & Humphreys, 1989). However, our study did not corroborate this finding. Our results showed the involvement of the same brain regions during the recognition of colored natural objects and colored artifacts. In general, object naming activated brain regions that extended from the occipital to the inferior temporal regions, including fusiform activation. These findings are consistent with earlier neuroimaging studies of object recognition (e.g., Grill-Spector, 2003; Price, Devlin, Moore, Morton, & Laird, 2005). Additionally, when compared to colored non-objects, colored objects (natural and artifacts) activated a more extensive network of brain regions that included the right parahippocampal gyrus (BA 35/36), the superior parietal lobule (BA 7; bilateral), the left inferior middle temporal region (BA 20/21) and the inferior and superior frontal regions (BA10/11/47). These additional activations were unique to colored objects and were not found when black and white objects were contrasted with black and white non-objects. These findings suggest that colored objects recruit brain regions that are related to visual semantic information, retrieval and visual-spatial processing. These findings are congruent with previous studies of colored object processing (Zeki & Marini, 1998).

Finally, in chapter 7, we attempted to reconcile the findings in the field by performing a meta-analysis of the literature concerning the effects of color information on object recognition. A significant effect of color information was found, clearly establishing the involvement of this visual attribute during object recognition processes. Additionally, this meta-analysis investigated the specific moderator role of other variables that might contribute to the effects of color on object recognition. Color diagnosticity level was the factor with the greatest moderator effect on the influence of color during object recognition: studies using color diagnostic objects show a strong significant effect of color (d = 0.43), whereas studies using non-color diagnostic objects show a marginally significant effect of color (d = 0.18). Moreover, we found that color information is an important cue for recognition of both natural and artifacts objects and objects presented as line-drawings or photographs.

8.2 General Discussion

Traditionally, object recognition models are edge-based, largely ignoring the influence of color information (Biederman, 1987; Marr & Nishihara, 1978). In the past twenty years, a number of neuroimaging, neurophysiological, and behavioral studies have shown that color information participates, at least to some degree, during object recognition (Tanaka, Weiskopf, & Williams, 2001). These findings, together with the fact that humans developed and retained visual mechanisms to support color vision (Gegenfurtner, 2003; Osorio & Vorobyev, 1996), makes the study of the effect of color information on object recognition worth to investigate in deep detail. A review of the literature yields mixed results, and no consensus has been reached concerning the role of color information in object recognition. The studies reported here make advances in the field and undoubtedly confirm the participation of color information during object recognition; however, our current comprehension of the visual conditions and the object types that may benefit from this visual attribute is far from complete.

One of the outcomes of this thesis is that, relative to color knowledge information, surface color information is more important during object recognition.

In chapter 2 and 3, we investigated whether surface color or color knowledge had a greater influence on object recognition. The results clearly show that the bottom-up influence of surface color plays a more prominent role, over the top-down color knowledge information, during object recognition. In chapter 2, we found that subjects took longer to say that the object name orange did not match with the picture of a carrot, only if the carrot was presented in a typical color format. This result shows that, when objects are not presented in a typical color, color knowledge information is not automatically activated by the object. Thus, the effect of color knowledge during object recognition is dependent on the presence of the typical color information in the object image. We can also speculate that the interference observed in this study when the objects were presented in a typical color format is due to the fact that the color knowledge information activated by the object name interfered with the surface color presented in the object shape, and that, not even in this condition, the color knowledge information was activated. That is, the color knowledge “orange” activated by the object name orange interfered with the surface color “orange” presented in the picture of a carrot (without the activation of the color knowledge information). In fact, in chapter 3, in the non-matching trials of the color knowledge verification task, we observed a strong interference of surface color in color knowledge. Subjects were slower to respond that the typical color of a mouse was not red when the mouse was presented in red compared to when it was presented in gray. It is possible that part of the interference observed in chapter 2 is actually caused by the interference of color knowledge activated by the object name and the surface color presented in the object picture. However, we also observed in chapter 3, that the surface color depicted on the objects promotes the activation of the color knowledge associated with that object. Subjects were slower to respond that the typical color of a strawberry was red when the strawberry was presented in gray compared to when it was presented in red. Although we cannot rule out the possibility that part of the interference observed in chapter 2 is actually caused by the interference of the color knowledge with the surface color, it is also caused by the interference between the color knowledge activated by the object name with the color knowledge activated by the object picture.

The results reported in chapter 3 also confirm that the surface color offers a greater input during object recognition processes when compared with color knowledge information. In this study, we found a clear interference and facilitation of the surface color information during the color knowledge verification. No interference or facilitation of the color knowledge information, however, was found during the surface color verification task. Two main contributions of surface color information in object recognition were reported here. First, surface color information is involved in matching the perceptual input with a structural description form stored in the long-term visual memory. Second, surface color information triggers the access and retrieval of semantic properties related to the object.

The current view in the literature is that color knowledge represents a more prominent source of information than does surface color (Joseph, 1997; Joseph & Proffitt, 1996). Joseph and collaborators (Joseph, 1997; Joseph & Proffitt, 1996) reported results from a series of verification tasks where they found that color knowledge is more influential during object recognition than is surface color. In their verification tasks, subjects were required to perform object verifications against three types of distractors: similar in shape and color, dissimilar in shape and color, and similar in shape but not in color. Because the visual system is a shape-driven system (Tanaka, Weiskopf, & Williams, 2001), the color interference observed in these previous studies was probably confounded with the interference of shape information. This fact is important because the effects of color and shape might not be additive; rather, it is plausible that shape and color similarly yield super-additive effects at the later stages of object recognition. In chapter 2, we added a fourth distractor (i.e., dissimilar in shape and similar in color), and we did not replicate these previous findings. Instead, we observed a superiority of surface color information over color knowledge information during object recognition processes.

Although we did not find any role of color knowledge in chapters 2 and 3, we do not discard the idea that color knowledge takes part in object recognition processes. In chapter 3, the electrophysiological brain responses associated with typical and atypical color objects were the same in the surface color verification task. This observation suggests that color knowledge information associated with the objects is not automatically activated when subjects did not need this information to perform the task. However, the surface color task was much easier than the color knowledge task; subjects performed the perceptual task within 350 ms after stimuli presentations in the surface color task, whereas there was a 650 ms lag for the color knowledge task. Moreover, the task did not require full activation of the object properties, and this fact might have masked the potential role of color knowledge information. Alternatively, it is unlikely that subjects do not activate any properties related to the presented objects. It is known that, 200-300 ms after stimuli onset, the functional and perceptive properties of the objects are automatically activated (Vihla, Laine, & Salmelina, 2006). At this point, the only claim that we can do is that color knowledge plays, at most, a very limited role during easy perceptual color verifications. However, we believe that this topic should be investigated further by employing more demanding perceptual color tasks. Actually, neuroimaging studies have reported an overlap in the brain regions responsible for color perception and color knowledge only if the perceptual color task is high demanding (e.g., Beauchamp, Haxby, Jennings, & DeYoe, 1999; Simmons et al., 2007). Neuroimaging studies have also elucidated the interactions between surface color and color knowledge. The current view in the literature is that the neural systems involved in color perception and stored color knowledge are distinct, but overlap in some neural regions. Although the posterior regions of fusiform gyrus (V4) and the occipital lingual gyrus are part of the color perception network (e.g., Zeki & Bartels, 1999; Zeki et al., 1991), the posterior ventral temporal cortex supports the color knowledge system (Chao & Martin, 1999; Wiggs, Weisberg, & Martin, 1999). These two systems interact in the fusiform gyrus; anterior to regions responsible for color perception, and posterior to regions supporting color knowledge retrieval (e.g., Simmons et al., 2007; Ueno et al., 2007). Martin (2007) suggests that this region in fusiform gyrus acts as a neural substrate for the acquisition of new object-color associations and allows these new representations to be utilized by the conceptual color processing system.

Another outcome of this thesis is the finding that the influence of color information on object recognition is dependent upon the object diagnosticity level. Tanaka and Presnell (1999) proposed that color information participates in object recognition only when objects are color diagnostic objects (see also, Nagai & Yokosawa, 2003; Oliva & Schyns, 2000). However, this theory is not empirically supported by recent studies showing a participation of color information in the recognition of both color and non-color diagnostic objects (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). Chapter 4 and 5 provide data that may help explaining these apparently contradictory results. These studies suggest that, during the recognition of color and non-color diagnostic objects, color information participates at different levels of visual processing. For the recognition of non-color diagnostic objects, color information was found to be an important cue for the initial image segmentation and visual input organization, thus, lowering the initial demand on the visual system. The results presented in chapter 4 show that reducing the demand of these initial processes makes the selection of a structural description form stored in the long-term visual memory easier and faster, resulting in faster object verifications. Moreover, these studies also show an absence of color effects for non-color diagnostic objects in the later stages of the visual process.

During color diagnostic object recognition, we observed additional roles for color information. Beyond the facilitation that color information confers to the initial visual stages, chapter 4 and 5 (and also chapter 3) showed a strong color effect in the later stages of object recognition. Our data suggest that color takes place in the later stages of the color diagnostic objects recognition in two different ways. First, color information triggers the selection of the structural object description model from the long-term visual memory to be matched to the perceptual input. When we see an object, color and shape are most likely processed in a parallel fashion. Some studies indicate that the same neural circuits, in the early visual cortical areas, processes information about color, shape and luminance (Gegenfurtner, 2003). At some point, this information must be combined to achieve a unitary and robust representation of the visual world. One possibility is that this information is combined during the structural description selection stage, where color might act as a cue to limits the range of candidate structural description forms. These data 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 participates in the activation and retrieval of the semantic network associated with these objects. The mechanisms involved in the participation of color in the activation and retrieval of the semantic network information of color diagnostic objects are not totally understood. The results presented in chapter 2 and 3 indicate that the color information presented in the object image activates the typical color that is associated with the objects. We postulate that other associative and functional properties are more easily accessed when objects are presented in a typical color format, making object recognition easier.

Color information appears to be important for the recognition of non-color diagnostic objects in the initial stages of the visual processing. If this is the case, why did we not observe an effect of color for these objects in the category and name verification tasks in chapter 4? Importantly, these tasks also required perceptual analyses. A possible explanation for the absence of a color effect in these tasks is that these tasks impose high processing demands at the semantic level; thus, the contribution of color information in the initial visual stages might be then diluted. This assumption presupposes that we should observe a strong color effect for non-color diagnostic objects in visual tasks having high initial perceptual demands and low semantic demands. Rather, our results suggest that tasks that impose high semantic demands will demonstrate a strong color effect for color diagnostic objects. This hypothesis requires further investigation.

Previous research has established a role for color information in the early and late visual processes of object recognition; however, these studies either did not control for the color diagnosticity status of the objects or only high-color diagnostic objects were used (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 information is considered to participate in object recognition in the later stages of the visual processing. In this model, the author proposed the existence of two separated representations for object structure *versus* object function information, termed *hasa* and *isa* representations, respectively. Object color, according to this model, is specifically part of the associated *hasa* properties, so that recognition of an object's color takes place after the initial visual representation has accessed the *hasa* color knowledge. The absence of color at the stored object structure was first disputed by Price and Humphreys (1989). The authors 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 dependents 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 data presented here advance our current understanding of the role of color information during object recognition and its relationship with the object's color diagnosticity status. The current view in the literature and the results described in chapter 4 and 5 are summarized in **Figure 8**. The information presented in the figure does not imply that the processing of color information or object recognition occurs in the serial fashion as depicted by the flowcharts. Moreover, we do not intend to put forth a new theoretical model or framework to explain how color information affects object recognition. The figure is simply a schematic illustration showing the main color effects encountered in our studies and considers the visual processing stages necessary to identify and name an object according to Humphreys and colleagues (Humphreys, Price, & Riddoch, 1999). The left side of the figure illustrates the recognition of a color diagnostic object in black-and-white and color formats. The right side of the image illustrates the recognition of a non-color diagnostic object presented in both black-and-white and color versions. The dotted and shorted arrows and boxes represent the processes and stages during which color information might help the recognition of both color and non-color diagnostic objects. Therefore, name representations that appear further to the bottom reflect the finding that more time is needed to recognize a black and white object. This illustration also explains why the effects of color during object recognition are stronger for color than non-color diagnostic objects (e.g., Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). However, we still need to investigate whether these color effects are dependent on the perceptual and semantic demands imposed by the visual tasks.

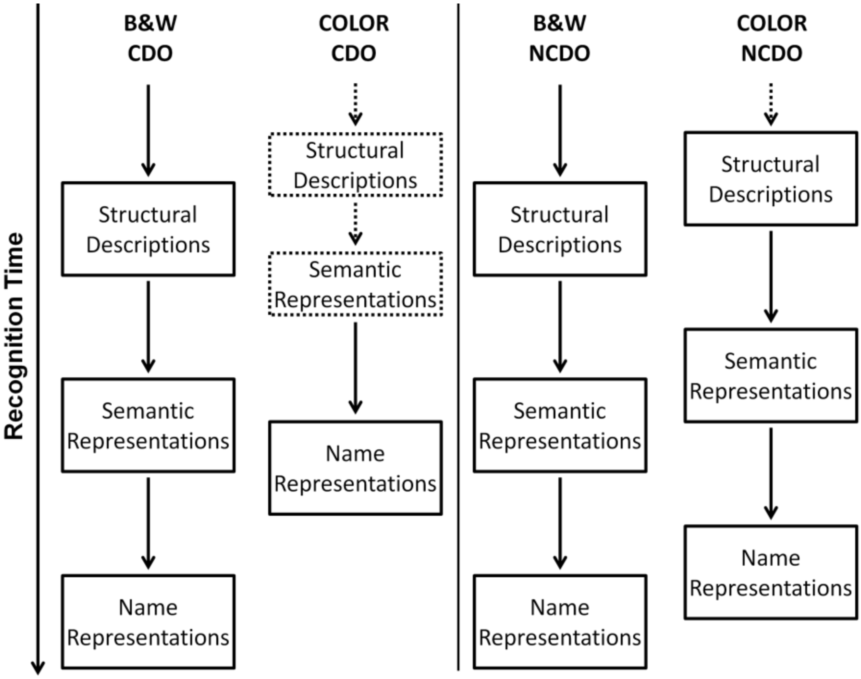

Figure 8. A schematic account for the processing of color information found in our studies. The visual processing stages depicted in the figure were proposed by Humphreys and colleagues (Humphreys, Price, & Riddoch, 1999). B&W CDO – color diagnostic object presented in black and white, COLOR CDO – color diagnostic object presented in colors, B&W NCDO – non-color diagnostic object presented in black and white, COLOR NCDO – non-color diagnostic object presented in colors. The dotted and shorted arrows and boxes represent the processes and stages where color information might aid recognition of both color and non-color diagnostic objects.

The interaction between color effects and the object's color diagnosticity status was also addressed in the meta-analysis presented in chapter 7. The meta-analysis showed a significant difference between the color effects observed in studies that used color diagnostic objects and studies that used non-color diagnostic objects. This is congruent with the results presented in chapters 4 and 5. Studies that used color diagnostic objects were found to have a strong effect of color; however, a marginally significant effect of color information was observed in studies that used non-color diagnostic objects.

The discussion of which object types might benefit from the presence of color information during recognition does not end with the object's color diagnosticity status. The impact of the semantic category has also been investigated. Previous studies have shown that color information improves the recognition of objects from natural but not artifacts categories (Humphreys, Goodale, Jakobson, & Servos, 1994; Mapelli & Behrmann, 1997; Price & Humphreys, 1989). Because objects from natural categories are more similar to each other, recognition requires a higher level of competition within the recognition system. Color information could help to resolve this competition. However, in this thesis, using a set of stimuli where color diagnosticity and structural similarity were controlled, we found no differences in the role of color information between natural objects and artifacts in both the behavioral and neuroimaging results. In chapter 6, we found that color information depicted in natural objects and in artifacts activated the same brain regions, suggesting that color has the same role in the recognition of natural objects and artifacts. This finding was replicated in chapters 2 and 4, where we observed that color information improved the recognition of both natural and artifacts objects. Moreover, in the meta-analysis performed in chapter 7, we found no differences regarding the color effects in studies that used natural and artifacts objects. In summary, color information improves both natural and artifacts objects (chapter 2 and 4) at the same levels of the visual recognition process (chapter 6). More recent studies that controlled for color diagnosticity level found the same pattern of results (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006).

Chapter 6 also discusses the neural regions involved in colored object recognition. Zeki and Marini (1998) proposed three broad cortical stages for color processing. The first, supported by V1 and V2, registers the presence and intensity of different wavelengths. The second, supported by V4, is involved in automatic color constancy operations. The third stage is related to the inferior temporal and frontal cortices and is involved in object color processing, memory, judgment and learning processes (Zeki & Marini, 1998). We corroborated these previous studies, showing that colored objects activated brain regions typically related to visual semantic information, retrieval and visuo-spatial processing (e.g., Ganis, Schendan, & Kosslyn, 2007; Oliver & Thompson-Schill, 2003; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996).

Another significant result of this work is the finding that color information plays the same role during the recognition of both types (line-drawings) and tokens (photographs). Uttl and colleagues (Uttl, Graf, & Santacruz, 2006) argue that line-drawings are typically viewed as a representation of an object class, a type, whereas photographs are viewed as a particular individual object, a token. To a certain extent, the recognition of types and tokens may recruit different perceptual and semantic processes, and color information could have different roles during the recognition of a type and a token. It might seem intuitive that color, combined with the additional surface information present in the photographs (e.g., texture and shadow), would have a greater effect. However, this question was explicitly addressed in chapter 4. We observed that color information affects types and tokens in the same way. Additionally, in chapter 7 we also observed similar color effects for studies using line-drawings and photographs. These results suggest that color, texture, and brightness information are processed during the same time-window, probably in a parallel fashion and that both surface attributes independently contribute to object recognition.

8.3 Future Directions

One important question that remains unanswered is the role that color knowledge plays during object recognition processes. We found a very limited role for this type of color information in chapters 2 and 3. However, we are not convinced that color knowledge information plays no role in object recognition. If this were the case, an atypical color object and a typical color object would be recognized as easier and faster. Moreover, we found strong color effects at the semantic level during color diagnostic object recognition. For color to improve color diagnostic object recognition at the semantic level, the color knowledge information for the objects needs to be activated. More research is needed to investigate the role of color knowledge and how it is activated during object recognition processes. It is also important to note that surface color and color knowledge information participate at different levels of visual processing during object recognition. Although surface color greatly contributes to the initial segmental and encoding stages, the role of color knowledge is most likely restricted to the later visual stages. Moreover, compared with simple identification or classification of isolated objects, color knowledge is likely to play a greater role during tasks involving memory recognition. Different and independent mechanisms have been proposed for object identification and object memory (Lloyd-Jones, 2005; Lloyd-Jones & Nakabayashi, 2009; Vernon & Lloyd-Jones, 2003). The distinction between object identification and memory recognition suggests that the former relies more on an achromatic description system and the latter relies on a surface-based episodic memory system that stores color information (Wichmann, Sharpe, & Gegenfurtner, 2002).

Another result that deserves further investigation was the absence of early effects (< 300 ms after stimulus onset) related to surface color information in chapter 3. In chapter 5 a strong color effect was observed around 100 ms after stimulus onset. The latter suggests that, when objects are presented in color, there is less demand placed on the initial visual processes. Importantly, there are methodological differences in the two studies. In chapter 3, we compared typical and atypical color presentations. In chapter 5, however, we compared typical color and black-and-white presentations. The absence of an early color effect in chapter 3 might be an indication that the presence of atypical color information also facilitates image segmentation by lowering the initial perceptual demands imposed by the visual recognition task. During early recognition processes, the visual system may not distinguish between typical and atypical colors. Furthermore, the surface color information present in the image may aid visual segmentation independent of its typicality for the object. To confirm this hypothesis, it would be necessary to compare object recognition during the three presentation modes in a single ERP experiment. In a recent study, Lu and collaborators (Lu et al., 2010) reported data that contradicts this assumption. The authors compared the ERP responses elicited by stimuli presented in typical, atypical, and black-and-white presentations. They showed that the early components (< 300 ms after stimuli onset) of atypical and black-and-white conditions essentially overlapped, suggesting that gray is processed as an incongruent color by the visual system. However, the authors used unnatural colors (e.g., fluorescent purple) to paint the atypical objects. This color scheme could have created perceptual demands as high as the black and white condition. In future research, the use of the same color for typical and an atypical object colors is needed to fully control for the effects of color frequency and typicality.

Although this thesis makes important advances in our understanding of the role of color in the recognition of color and non-color diagnostic objects, we believe that additional research is needed to corroborate these initial studies. For example, the participation of color information during the activation and retrieval of semantic networks related to recognition of color diagnostic objects needs further investigation. Here we observed that, when compared with black and white objects, a more extensive semantic brain network is involved during the recognition of colored objects (chapter 6). In addition, strong color effects in ERP components are related to semantic processing (N400 and LPC; chapters 3 and 5). Furthermore, color information improves object recognition during tasks with high semantic demands (chapter 4). These results suggest that color information is involved at the semantic level during the recognition of color diagnostic objects. However, at the present moment, we do not have a clear picture of how this process takes place. For color to improve recognition of color diagnostic objects at the semantic level, the relationship between the color and the object's identify must be, at least to some extent, previously determined. Most likely, an object's color identity is processed in parallel or in cascade with other visual or semantic features of the objects. If the relationship between color and shape is strong, the semantic network that is related to the objects is more readily and rapidly activated. Chapter 2 and 3 also suggest that surface color information prompts activation of color knowledge in the cognitive system. We postulate that the activation of color knowledge information triggers access to other functional and associative properties. However, this hypothesis needs further investigation.

Although we focused our studies on the effect of color during object recognition, it would be interesting to evaluate whether these results can also be generalized to recognition of visual scenes or other types of objects, such as faces. Indeed, a number of models of scene recognition have argued that surface-based cues are used to categorize scenes (scene *gist*) without the need to identify particular objects within those scenes (Oliva & Schyns, 1997, 2000). During face processing, research has shown that surface color can assist in the discrimination of gender, particularly when other cues, such as the shape of the face, are non-predictive (Tarr, Kersten, Cheng, Doerschner, & Rossion, 2002; Tarr, Kersten, Cheng, & Rossion, 2001).

Additionally, the role of surface texture also merits further exploration. Studies indicate that color and texture information are processed independently (e.g., Cant, Arnott, & Goodale, 2009), although the extraction of color information seems to occur relatively early in visual analysis when compared with surface textures.

8.4 Conclusions

In summary, the general picture that emerges from this work is that color information participates in object recognition processes. Although it was outside the scope of this thesis to provide a new model of object recognition, this work helps to establish certain principles that future successful models of color information must incorporate. First, the role of surface color is more influential than the role of color knowledge during recognition of color diagnostic objects. Second, color information improves the recognition of color and non-color diagnostic objects at different stages of the visual processing. Although color is an important cue for both object types during early visual processes, it is also important for recognition of color diagnostic objects in the late stages of the visual processing. Namely, color information aids in the selection of a structural description model that matches the perceptual input and participates in the access and activation of the semantic network associated with these objects. Third, color information improves the recognition of natural and artifacts objects as well as objects presented as *types* (line-drawings) and *tokens* (photographs). It is clear that color influences object processing at multiple levels of representation. The challenge now is to determine more precisely how color, and perhaps also texture, combine with object shape when we identify and recall previously encountered objects.

Resumo em Português

Resumo

O ser humano tem uma capacidade incrível para reconhecer objectos. As propriedades específicas que são extraídas do ambiente visual, e a forma como essas propriedades se integram para resultar num reconhecimento rápido e eficaz são ainda um mistério para as Ciências Cognitivas. Sabemos que, para além da forma, o sistema visual utiliza informação sobre movimento, cor, textura, entre outras propriedades, para reconhecer os objectos que nos rodeiam. O trabalho aqui apresentado procura esclarecer o papel da cor no reconhecimento visual de objectos.

Se considerarmos que o cérebro humano desenvolveu mecanismos especializados para lidar com a cor, faz sentido questionarmo-nos sobre o papel que essa informação poderá ter no reconhecimento visual de objectos. A retina humana está equipada com três tipos de cones, permitindo ao ser humano uma visão tricromática. A maioria dos mamíferos possui unicamente um ou dois tipos de cone na retina, sendo apenas os humanos e alguns primatas a possuir visão tricromática. Qual será a vantagem evolutiva deste tipo de visão? Um ponto de vista é que a visão tricromática teria evoluído para facilitar a procura de alimentos, pois permite detectar mais facilmente folhas e frutos maduros (e.g., Osorio & Vorobyev, 1996; Regan et al., 2001). Apesar desta vantagem evolutiva óbvia, as teorias sobre o reconhecimento visual de objectos têm negligenciado o potencial papel da cor no reconhecimento (Biederman, 1987; Marr & Nishihara, 1978). No entanto, actualmente há alguma concordância na literatura relativamente ao contributo da cor para o reconhecimento de objectos: objectos apresentados a cores são reconhecidos mais rapidamente que objectos apresentados a preto e branco (ver, para uma revisão, Tanaka, Weiskopf, & Williams, 2001). Desta forma, faz sentido investigar e aprofundar o conhecimento existente sobre o papel do atributo cor no reconhecimento visual de objectos.

Neste contexto é importante diferenciar entre o atributo visual cor presente na imagem de um objecto (e.g., um morango pintando de vermelho) e o

conhecimento de cor activado quando se vê a imagem de um objecto (e.g., perante uma imagem de um morango a preto e branco, o conhecimento da cor típica do morango pode ser activado). Na primeira situação fala-se de cor de superfície e na segunda fala-se de conhecimento de cor. Tanaka, Weiskopf e Williams (2001) sugeriram que a cor participa no reconhecimento de objectos através de mecanismos *bottom-up* (cor de superfície) e de mecanismos *top-down* (conhecimento de cor). No entanto, fica ainda por esclarecer quais destas duas informações de cor é a mais determinante durante os processos de reconhecimento de objectos ou como é que estas duas fontes de informação interagem de modo a reconhecer um objecto. Assim, um dos objectivos deste trabalho foi tentar clarificar estas questões. Nos capítulos 2 e 3 estudámos como é que estas duas fontes de informação relativas à cor interagem e qual delas é a mais determinante durante os processos de reconhecimento visual de objectos.

No estudo apresentado no capítulo 2, investigámos se o papel do conhecimento de cor é independente da cor de superfície, ou seja, tentámos perceber se o conhecimento de cor é activado no sistema cognitivo independentemente da presença a cor de superfície. Joseph e colaboradores (Joseph, 1997; Joseph & Proffitt, 1996) mostraram previamente que o conhecimento de cor é mais determinante durante o reconhecimento visual de objectos do que a cor de superfície. No entanto, nestes estudos os papéis da cor e da forma não foram testados de uma forma completamente independente, o que poderá camuflar os resultados obtidos (Joseph, 1997; Joseph & Proffitt, 1996). Neste sentido, pretendemos replicar estes resultados no capítulo 2, manipulando o papel da cor e da forma de modo independente. Pedimos a um grupo de participantes para verificarem se um nome previamente apresentado correspondia ou não a uma imagem que se lhe seguia. Estas imagens eram fotografias de objectos comuns e foram apresentadas na sua cor típica, a preto e branco e numa cor atípica. O tempo de resposta dos participantes nos ensaios negativos (ou seja, quando nome e objecto não correspondiam) foi utilizado para avaliar se existia interferência na resposta. Partiu-se do princípio que quanto mais similares fossem o objecto representado pelo nome e o objecto representado pela fotografia (em termos de cor e forma), mais tempo os participantes demorariam a responder que nome e objecto correspondiam a objectos diferentes. De modo a verificar a interferência da cor independentemente da forma, definiram-se quatro tipos de ensaios negativos: forma e cor semelhantes (morango-tomate), forma semelhante e cor diferente (limão-cebola), forma diferente e cor semelhante (cenoura-laranja), e forma e cor diferentes (ananás-pêra). Se o conhecimento de cor for activado independentemente da presença de cor de superfície no objecto, então espera-se observar maior interferência quando o conhecimento de cor activado pelo nome corresponda ao conhecimento de cor activado pelo objecto, não só quando o objecto for apresentado na sua cor típica, mas também quando for apresentado numa versão a preto e branco ou numa cor atípica.

Os nossos resultados mostraram um efeito acentuado da semelhança de cor e de forma quando os objectos eram apresentados na sua cor típica, ou seja, os participantes eram mais lentos a dizer que nome e objecto não correspondiam quando estes partilhavam características de cor e de forma. No entanto, quando os objectos foram apresentados a preto e branco ou numa cor atípica, a interferência devida à semelhança de cor desapareceu, permanecendo apenas a interferência devida à semelhança de forma. Estes resultados mostraram que o conhecimento de cor de um objecto não é automaticamente activado e que está fortemente dependente da presença de cor de superfície. Assim, os resultados deste estudo sugerem que a influência da cor de superfície é mais determinante durante o reconhecimento visual de objectos do que o conhecimento de cor.

No capítulo 3, continuámos a investigar esta questão. O estudo apresentado neste capítulo recorre a medidas comportamentais (tempos de resposta) e electrofisiológicas (Potencias Evocados) para investigar a interacção entre a cor de superfície e o conhecimento de cor durante o reconhecimento de objectos. Os potenciais evocados permitem a análise dos processos cognitivos com uma resolução temporal na ordem dos milissegundos, constituindo assim a técnica ideal para investigar o momento em que o sistema visual recruta a cor de superfície e o conhecimento de cor durante o reconhecimento de objectos.

Neste estudo foi pedido aos participantes para efectuarem duas tarefas de verificação cor-objecto: uma tarefa de verificação de conhecimento de cor, onde os participantes deveriam decidir se a cor típica do objecto apresentado correspondia ou não a uma determinada cor, independentemente da cor com que o objecto aparecia apresentado; e uma tarefa de verificação de cor de superfície, em que os participantes deveriam decidir se a cor com que o objecto era apresentado correspondia ou não a uma determinada cor, independentemente da cor típica do objecto. Os objectos foram apresentados numa cor típica e numa cor atípica, de forma a avaliar o papel da cor de superfície e do conhecimento de cor durante o reconhecimento. Como forma de verificar o contributo/interferência da cor de superfície durante a tarefa de conhecimento de cor e o contributo/interferência do conhecimento de cor durante a tarefa de cor de superfície, os potenciais evocados pelos objectos de cor típica e atípica foram comparados nas duas tarefas de verificação.

Na tarefa de verificação de conhecimento de cor, observámos um efeito da cor em dois componentes da resposta electrofisiológica ao estímulo: o N350 e o *Late Positive Complex* (LPC). O N350 é um componente com uma distribuição frontal negativa que ocorre por volta dos 300 milissegundos depois do aparecimento do estímulo. Este componente é considerado a primeira marca do reconhecimento visual e é indicativo da selecção de um modelo armazenado em memória a longo termo que melhor corresponde com o *input* visual, sendo mais negativo para objectos apresentados em formas atípicas (Pietrowsky et al., 1996; Schendan & Kutas, 2002, 2003, 2007). O LPC é um componente com uma distribuição positiva que ocorre 550 milissegundos depois do aparecimento do estímulo. É também mais negativo para objectos mais difíceis de reconhecer do que para objectos mais fáceis de reconhecer e reflecte a activação do conhecimento semântico e associativo relacionado com os objectos (Mazerolle, D'Arcy, Marchand, & Bolster, 2007; Pietrowsky et al., 1996; Schendan & Kutas, 2002, 2003, 2007; Stuss, Picton, Cerri, Leech, & Stethem, 1992). Os efeitos de cor encontrados nestes dois componentes na tarefa de verificação de conhecimento de cor sugerem que a cor de superfície contribui e influencia a verificação do conhecimento de cor dos objectos pelo menos de duas formas. Primeiro, facilitando a selecção de um modelo armazenado em memória para corresponder com o *input* visual, e segundo, contribuindo para a activação da rede semântica relacionada com os objectos. Os resultados comportamentais corroboraram os resultados electrofisiológicos: observámos um efeito forte da cor de superfície durante a tarefa de verificação de conhecimento de cor. Os participantes são mais rápidos a decidir que a cor típica de um morango é vermelho quando o morango está apresentado a vermelho do que quando está apresentado a cinzento. Da mesma forma, os participantes são mais rápidos a decidir que a cor típica de um morango não é cinzento quando o morango está apresentado a vermelho do que quando está apresentado a cinzento.

Na tarefa de verificação de cor de superfície não se verificaram quaisquer diferenças nos potenciais evocados por objectos apresentados na cor típica e atípica, mostrando que não há participação do conhecimento de cor nesta tarefa. Mais uma vez os resultados comportamentais corroboraram os resultados electrofisiológicos, não se tendo observado nenhum efeito do conhecimento de cor na tarefa de cor de superfície. Os participantes são igualmente rápidos a decidir que um morango vermelho (objecto tipicamente vermelho) e um rato vermelho (objecto que não é tipicamente vermelho) estão apresentados a vermelho e a decidir que um morango cinzento (objecto tipicamente vermelho) e um rato cinzento (objecto que não é tipicamente vermelho) não estão apresentados a vermelho. Estes resultados mostram que o papel do conhecimento de cor é limitado durante o reconhecimento visual de objectos.

De um modo geral, os estudos apresentados nos capítulos 2 e 3 mostram que durante o reconhecimento visual de objectos o papel da cor de superfície é mais determinante que o papel do conhecimento de cor.

Outra das questões investigadas nesta tese foi o estudo do tipo de objectos cujo reconhecimento visual beneficia com a presença de cor, procurando-se identificar o estádio do processamento visual onde a informação sobre cor é recrutada durante o processo de reconhecimento. Os resultados que emergem da literatura relativamente a estas questões são pouco consistentes. Por exemplo, há estudos que afirmam que a cor apenas facilita o reconhecimento de objectos que pertencem a categorias semânticas biológicas (Price & Humphreys, 1989) ou de objectos que têm cor diagnóstica (i.e., objectos que estão altamente associados a uma cor particular; Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999). Contudo, outros autores argumentam que a cor facilita o reconhecimento de todos os objectos, independentemente da sua categoria semântica ou da diagnosticidade da sua cor (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006). As razões desta discrepância de resultados podem estar relacionadas com o estádio do processamento visual em que a cor intervém para facilitar o reconhecimento de objectos de cor diagnóstica e não diagnóstica. Há estudos que mostram que a cor participa nos estádios iniciais do processamento visual (Gegenfurtner & Rieger, 2000; Wurm, Legge, Isenberg, & Luebker, 1993), facilitando a segmentação da imagem, e/ou ao nível semântico, onde a activação da cor pode facilitar a activação do conhecimento semântico sobre os objectos (Davidoff, 1991; Tanaka, Weiskopf, & Williams, 2001).

Nos capítulos 4 e 5 deste trabalho, testámos a hipótese de que a cor de superfície participa em etapas diferentes durante o reconhecimento de objectos com cor diagnóstica e não diagnóstica. Como referimos, os objectos com cor diagnóstica estão fortemente associados a uma cor. Neste caso, faz sentido que a informação de cor participe na activação da rede semântica associada a estes objectos, facilitando o seu reconhecimento. Pelo contrário, como os objectos com cor não diagnóstica não estão associados a uma cor particular, não faz sentido que a informação de cor providencie uma pista importante durante as etapas mais tardias do reconhecimento. Assim, esperamos que a cor de superfície participe no reconhecimento de objectos com cor diagnóstica quer nos estádios iniciais do processamento visual, quer em estádios mais tardios. No entanto, esperamos que o papel da cor durante o reconhecimento de objectos com cor não diagnóstica esteja limitado aos estádios iniciais do processamento visual.

No estudo apresentado no capítulo 4, os participantes realizaram três tarefas de reconhecimento visual, onde objectos com cor diagnóstica e não diagnóstica foram apresentados na sua cor típica e a preto e branco: tarefa de verificação de nome, tarefa de verificação de categoria, e tarefa de verificação de objecto. Estas três tarefas de reconhecimento visual implicam exigências e processamentos cognitivos distintos (Humphreys, Price, & Riddoch, 1999). Na tarefa de verificação de nome era pedido aos participantes para verificarem se o objecto correspondia ou não a um nome previamente apresentado. Para o desempenho desta tarefa é necessário, numa primeira etapa, que a imagem do objecto seja segmentada de forma a ser emparceirada com um modelo armazenado na memória a longo termo. Seguidamente os participantes têm que aceder às propriedades semânticas dos objectos e só depois o nome do objecto poderá ser activado. Na tarefa de verificação de categoria era pedido aos participantes para verificarem a categoria semântica dos objectos (biológico *versus* não-biológico). Para realizarem esta tarefa os participantes não necessitam de aceder à representação do nome dos objectos. Finalmente, na tarefa de verificação de objecto era pedido aos participantes para verificar se o objecto apresentado era um objecto familiar ou não (objecto *versus* não-objecto). Para efectuarem esta tarefa os participantes não necessitam de aceder nem ao nome, nem à informação semântica associada aos objectos apresentados. Esta tarefa implica apenas a segmentação da imagem e a sua correspondência com um modelo armazenado em memória a longo termo. A comparação dos tempos de resposta, nas três tarefas, entre objectos apresentados a cores e a preto e branco permite-nos verificar onde é que a informação de cor é recrutada durante o reconhecimento de objectos com cor diagnóstica e não diagnóstica.

Os resultados mostraram que apenas na tarefa de verificação de objecto se observa um efeito de cor no reconhecimento de objectos com cor não diagnóstica. Pelo contrário, o efeito da cor para objectos com cor diagnóstica foi mais forte durante as tarefas de verificação de categoria e de verificação de nome. Estes resultados sugerem que o papel da cor no reconhecimento de objectos de cor não diagnóstica está limitado a um nível pré-semântico. No entanto, durante o reconhecimento de objectos de cor diagnóstica, o atributo cor revelou-se mais importante a um nível semântico.

No capítulo 5, esta questão continuou a ser investigada, mas desta vez recorrendo a medidas electrofisiológicas. Neste estudo também foram apresentados aos participantes imagens de objectos com cor diagnóstica e não diagnóstica tanto na sua cor típica como a preto e branco. Os potenciais evocados pelas imagens a cores e a preto e branco foram comparados em três componentes electrofisiológicos: N1, N350 e N400. O N1 é um componente electrofisiológico que atinge o seu pico máximo aproximadamente 150 milissegundos após o aparecimento do estímulo e é mais visível nas regiões occipito-temporais. Este componente está associado aos estádios de processamento visual iniciais e é maior tanto mais negativo quanto maior for a exigência do processamento visual (Johnson & Olshausen, 2003; Kiefer, 2001; Rossion et al., 2000; Tanaka, Luu, Weisbrod, & Kiefer, 1999; Wang & Kameda, 2005; Wang & Suemitsu, 2007). Os componentes N350 e N400 são componentes relacionados com estádios de reconhecimento mais tardios. Como foi descrito anteriormente, o N350 é um componente negativo com uma distribuição topográfica anterior e é considerado o primeiro sinal de sucesso no reconhecimento (Barrett & Rugg, 1990; McPherson & Holcomb, 1999; Pratarelli, 1994). O N350 é seguido do N400 que se caracteriza por uma deflexão negativa nas regiões centro-parietais com amplitude máxima por volta dos 400 milissegundos depois do aparecimento do estímulo. O N400 é um indicador de processamento semântico e é maior (ou seja, mais negativo) para estímulos semanticamente não relacionados do que para estímulos semanticamente relacionados (Kutas & Hillyard, 1980a, 1980b).

Os nossos resultados mostraram um efeito de cor para os objectos com cor diagnóstica e não diagnóstica no componente N1. Os potenciais evocados pelos objectos apresentados a preto e branco apresentaram um N1 mais negativo do que os objectos apresentado a cores, sugerindo que a cor diminui as exigências dos estádios iniciais de processamento visual em ambos os tipos de objectos. Observámos ainda um efeito de cor nos componentes N350 e N400 apenas para aos objectos com cor diagnóstica. Este resultado mostra que a participação da cor em estádios de processamento visual mais tardios está restrita ao reconhecimento de objectos com cor diagnóstica.

De um modo geral, os resultados dos estudos apresentados nos capítulos 4 e 5 mostram que a cor de superfície tem diferentes papéis durante o reconhecimento de objectos com cor diagnóstica e não diagnóstica. Durante o reconhecimento de ambos os tipos de objectos a cor mostrou ser uma informação importante durante as etapas iniciais de processamento visual, provavelmente ajudando a segmentar a imagem e a extrair a forma do objecto. Para além disso, a cor tem um papel nos estádios de processamento visual mais tardios, mas apenas para os objectos com cor diagnóstica. Primeiro, facilita a selecção de um modelo da memória a longo termo para corresponder com o *input* fornecido pela imagem do objecto. Este resultado pode ser indicativo de que os modelos correspondentes aos objectos de cor diagnóstica estão armazenados num formato colorido. Segundo, a cor mostrou ser um atributo que actua ao nível semântico, activando a rede semântica associada aos objectos de cor diagnóstica e fazendo com que o seu reconhecimento e identificação sejam mais eficazes.

No capítulo 6 deste trabalho continuámos a investigar quais os objectos cujo reconhecimento beneficia com a presença de cor, procurando identificar as áreas cerebrais envolvidas no processamento da cor durante o reconhecimento visual de objectos. Com o objectivo de investigar se o atributo visual cor beneficia apenas os objectos pertences a categorias semânticas biológicas (Price & Humphreys, 1989), os participantes deste estudo nomearam objectos de categorias biológicas e não biológicas apresentados a cores e a preto e branco enquanto as respostas cerebrais hemodinâmicas eram medidas através da técnica de imagem de ressonância magnética funcional. Os resultados mostraram que ambos os tipos de objectos activavam uma rede cerebral mais extensa quando apresentados a cores do que quando apresentados a preto e branco, rede esta que englobava a circunvolução parahipocampal direita (BA 35/36), o lóbulo parietal superior bilateralmente (BA 7), a região temporal inferior esquerda (BA 20/21) e ainda regiões frontais superiores (BA 10/11/47). Estas activações indicam que o processamento de objectos a cores activa regiões cerebrais responsáveis pelo armazenamento e recuperação de informação visuo-semântica e regiões responsáveis pelo processamento visuo-espacial. Mais uma vez, os resultados mostram o envolvimento da cor ao nível da activação da rede semântica relacionada com os objectos e mostram ainda que o papel da cor é independente da categoria semântica à qual pertencem os objectos.

Por fim, procurando chegar a algum consenso relativamente ao papel da cor do reconhecimento de objectos, efectuámos uma meta-análise no capítulo 7 deste trabalho. Nesta meta-análise incluímos 35 estudos independentes, englobando um total de 1535 participantes, onde o papel da cor no reconhecimento de objectos foi investigado. Encontrámos um efeito moderado e significativo do papel da cor no reconhecimento de objectos (d = 0.28). O efeito específico de uma série de variáveis moderadoras também foi investigado. Verificámos que a diagnosticidade de cor é o factor com efeito moderador mais forte: nos estudos que utilizam objectos com cor diagnóstica encontrámos um efeito forte e significativo da cor (d = 0.43); no entanto, em estudos que utilizam objectos com cor não diagnóstica, o efeito da cor foi apenas marginalmente significativo (d = 0.18). Para além disso, verificámos que a cor é importante quer para reconhecer objectos pertencentes a categorias biológicas quer para reconhecer objectos de categorias não biológicas, e também igualmente importante no reconhecimento de objectos apresentados através de fotografias ou de desenhos. Os resultados desta meta-análise apontam para o facto da cor desempenhar um papel preponderante no reconhecimento visual de objectos, mostrando que esta propriedade deve ser tida em conta nos modelos teóricos que pretendem descrever este processo cognitivo.

De um modo geral, este trabalho confirma a importância do atributo cor no reconhecimento visual de objectos. Apesar de não ser ambição deste trabalho avançar com um modelo teórico explicativo do papel da cor no reconhecimento de objectos, são aqui estabelecidos uma série de princípios que qualquer modelo futuro deverá considerar. Primeiro, a cor de superfície parece ter um papel mais relevante no reconhecimento de objectos do que o papel do conhecimento de cor. Segundo, a cor intervém no reconhecimento de objectos a diferentes níveis do processamento visual. Assim, a informação visual de cor mostrou ser importante durante os primeiros estádios de processamento visual tanto para reconhecer objectos com cor diagnóstica como para reconhecer objectos com cor não diagnóstica. No entanto, o envolvimento da cor nos estádios de processamento visual mais tardios está limitado ao reconhecimento de objectos com cor diagnóstica, para os quais a cor pode ser uma pista importante para limitar o número de modelos compatíveis com o *input* visual, podendo também facilitar a activação e recuperação de informação semântica relacionada com este tipo de objectos. Terceiro, a cor facilita quer o reconhecimento de objectos biológicos, quer o reconhecimento de objectos não biológicos e o reconhecimento de objectos apresentados em desenhos e em fotografias. Neste momento acreditamos que a cor influencia o reconhecimento visual de objectos em múltiplos níveis do processamento. O desafio agora é determinar de um modo mais preciso como cor e forma interagem quando temos que reconhecer e identificar objectos previamente encontrados.

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Appendix

Appendix A – Stimuli used in the study reported in Chapter 3

Color	Object Name
Red	Apple, Cherry, Heart, Lips, Strawberry, Tomato, Ladybug
Gray	Key, Mouse, Nail, Scissors, Hippopotamus, Shark, Elephant
Orange	Carrot, Lobster, Orange, Pineapple, Pumpkin, Crab, Traffic cone
Green	Alligator, Artichoke, Frog, Lettuce, Pepper, Tree, Pea
Yellow	Banana, Bee, Lemon, Star, Sun, Cheese, Bird
Brown	Camel, Deer, Fox, Kangaroo, Monkey, Peanut, Nut
Pink	Arm, Ear, Finger, Pig, Leg, Hand, Foot
White	Cigarette, Cloud, Sheep, Swan, Bone, Igloo, Tooth

Appendix B – Stimuli used in the study reported in Chapter 4

Color Diagnostic Objects

Object Name	Color	Diagnosticity	Object Name	Color	Diagnosticity
Banana	Yellow	4.53	Lemon	Yellow	4.80
Barrel	Brown	4.07	Lettuce	Green	4.47
Basket Ball	Orange	4.40	Light Bulb	Glass	4.33
Bathing-tub	Beige	4.07	Nail	Gray	4.33
Binoculars	Black	4.07	Nut	Brown	4.60
Broccoli	Green	4.53	Onion	Golden	4.60
Carrot	Orange	4.73	Orange	Orange	4.73
Cherry	Red	4.60	Padlock	Golden	4.07
Chick	Yellow	4.33	Peanut	Brown	4.40
Cigar	Brown	4.13	Pig	Pink	4.33
Crab	Orange	4.53	Pineapple	Orange	4.73
Door	Brown	4.20	Pipe	Brown	4.07
Dresser	Brown	3.93	Pumpkin	Orange	4.47
Fire Extinguisher	Red	4.40	Strawberry	Red	4.67
Grapes	Purple	4.13	Table	Brown	4.20
Guitar	Brown	4.13	Tire	Black	4.47
Hammer	Brown	4.07	Tomato	Red	4.67
Kangaroo	Brown	4.33	Watermelon	Red	4.53

Non-Color Diagnostic Objects

Object Name	Color	Diagnosticity	Object Name	Color	Diagnosticity
Apple	Red	3.13	Funnel	Black	2.53
Bear	Brown	3.67	Glass	Glass	2.67
Beret	Orange	1.93	Glasses	Brown	1.80
Bicycle	Black	1.93	Glove	Pink	1.27
Book	Orange	2.07	Horse	Brown	2.87
Boot	Brown	1.60	Lamp	Golden	1.87
Bottle	Golden	2.67	Leaf	Green	2.87
Bowl	Purple	1.53	Mushroom	Brown	2.93
Bucket	Orange	1.47	Pen	Orange	1.87
Butterfly	Red	1.80	Pepper	Green	3.67
Candle	Red	2.27	Rabbit	Brown	2.93
Cat	Gray	2.47	Shirt	Red	1.27
Chicken	Beige	3.27	Snake	Brown	3.41
Comb	Yellow	1.47	Sock	Yellow	2.40
Cow	Brown	2.93	Tie	Yellow	1.47
Cup	Orange	1.93	Tulip	Red	2.87
Duck	Brown	2.67	Turtle	Brown	2.67
Fish	Orange	2.53	Watering Can	Brown	2.13

Appendix C – Stimuli used in the study reported in Chapter 5

Color Diagnostic Objects

Object Name	Color	Diagnosticity	Object Name	Color	Diagnosticity
Banana	Yellow	4.53	Kangaroo	Brown	4.33
Barrel	Brown	4.07	Ladybug	Red	4.67
Basket Ball	Orange	4.40	Lemon	Yellow	4.80
Bathing-tub	Beige	4.07	Lettuce	Green	4.47
Bee	Yellow	4.27	Light Bulb	Glass	4.33
Binoculars	Black	4.07	Lips	Red	4.46
Bone	White	4.30	Lobster	Orange	4.73
Bonfire	Red	4.20	Nail	Gray	4.33
Brick	Orange	4.60	Nut	Brown	4.60
Broccoli	Green	4.53	Octopus	Purple	4.80
Carrot	Orange	4.73	Onion	Golden	4.60
Cherry	Red	4.60	Orange	Orange	4.73
Chick	Yellow	4.33	Padlock	Golden	4.07
Cigar	Brown	4.13	Pea	Green	4.80
Cigarette	White	4.82	Peanut	Brown	4.40
Crab	Orange	4.53	Pear	Green	4.13
Door	Brown	4.20	Pig	Pink	4.33
Dresser	Brown	3.93	Pineapple	Orange	4.73
Eggplant	Purple	4.40	Pipe	Brown	4.07
Fire Extinguisher	Red	4.40	Pumpkin	Orange	4.47
Fox	Brown	4.27	Strawberry	Red	4.67
Garlic	White	4.40	Table	Brown	4.20
Grapes	Purple	4.13	Tire	Black	4.47
Guitar	Brown	4.13	Tomato	Red	4.67
Hammer	Brown	4.07	Traffic Cone	Orange	4.50
Hand	Pink	4.18	Traffic Signal	Red	4.20
Harp	Golden	4.07	Watermelon	Red	4.53

Non-Color Diagnostic Objects

Object Name	Color	Diagnosticity	Object Name	Color	Diagnosticity
Apple	Red	3.13	Funnel	Black	2.53
Balloon	Red	1.36	Glass	Glass	2.67
Bear	Brown	3.67	Glasses	Golden	1.80
Beret	Orange	1.93	Glove	Pink	1.27
Bicycle	Black	1.93	Horse	Brown	2.87
Bird	Brown	2.00	Lamp	Golden	1.87
Book	Orange	2.07	Leaf	Green	2.87
Boot	Yellow	1.60	Monkey	Brown	3.55
Bottle	Golden	2.67	Mushroom	White	2.93
Bow	Red	1.07	Pen	Brown	1.87
Bowl	Purple	1.53	Pepper	Green	3.67
Box	Orange	1.18	Purse	Purple	1.00
Brush	Orange	1.80	Rabbit	Brown	2.93
Bucket	Orange	1.47	Racket	White	2.40
Butterfly	Red	1.80	Scarf	Purple	1.00
Candle	Red	2.27	Shirt	Red	1.27
Carnation	Red	3.50	Shoe	Red	1.87
Cat	Gray	2.47	Shovel	Yellow	2.43
Chicken	Beige	3.27	Skirt	Green	1.00
Comb	Red	1.47	Snake	Brown	3.41
Cow	Brown	2.93	Sock	Green	1.40
Cup	Orange	1.93	Sofa	Yellow	1.80
Dice	White	3.40	Tie	Yellow	1.20
Dog	Brown	2.91	Tulip	Pink	2.13
Dress	Orange	1.20	Turtle	Brown	3.40
Duck	Brown	2.67	Umbrella	Orange	1.20
Fish	Brown	2.53	Watering Can	Orange	1.87

Appendix D – Stimuli used in the study reported in Chapter 6

Natural objects	Artifacts objects
Alligator	Accordion
Ant	Airplane
Apple	Anchor
Bear	Barrel
Butterfly	Basket
Chicken	Bell
Cow	Belt
Dog	Boot
Duck	Bus
Fox	Car
Gorilla	Cigarette
Grapes	Drum
Horse	Flute
Lemon	Fork
Monkey	Glasses
Mushroom	Gun
Onion	Hammer
Pear	Harp
Pepper	Key
Pig	Nail
Potato	Needle
Rabbit	Nut
Rooster	Pencil
Seal	Piano
Squirrel	Scissors
Strawberry	Shoe
Tiger	Spoon
Turtle	Thimble