ELECTROPHYSIOLOGICAL EVIDENCE FOR COLOR EFFECTS ON THE RECOGNITION OF COLOR DIAGNOSTIC AND NON-COLOR DIAGNOSTIC OBJECTS

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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 naming task in which colored and black-and-white versions of both types of objects were presented. The black-and-white and the color presentations were compared in two groups of event-related potentials (ERPs): (1) the P1 and N1 components, indexing early visual processing; and (2) the N400 component, which index late visual processing. A color effect was observed in the P1 and N1 components, for both color and non-color diagnostic objects. In addition, for color diagnostic objects, a color effect was observed in the N400 component. These results suggest that color information is important for the recognition of color and non-color diagnostic objects at different levels of visual processing. It thus appears that the visual system uses color information, during recognition of both object types, at early visual stages; however for the color diagnostic objects recognition, color information is also recruited during the late visual processing stages.

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INTRODUCTION

There is a large body of research suggesting that color information plays a role in object recognition (for a review, see Tanaka, Weiskopf, & Williams, 2001). However, the processing stage at which this occurs and the types of objects that might be more efficiently identified by color processing are both matters of debate. Attempts to address this issue have primarily focused on color diagnosticity, which refers to the degree to which a particular object is associated with a specific color (Tanaka & Presnell, 1999). 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 results suggest that color information improves object recognition independent of color diagnosticity (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006), other results indicate that color only improves the recognition of color diagnostic objects (Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999).

In a previous behavioral study, we reported results which suggest 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, while for non-color diagnostic objects, color plays a role at a pre-semantic recognition level (Bramão, Inácio, Faísca, Reis, & Petersson, 2011). In this study, we built on these results in an electroencephalogram (EEG) experiment. Unlike behavioral measures, event-related potentials (ERPs) allow for the analysis of electrophysiological signatures of cognitive processes with high temporal resolution at the millisecond time-scale. 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 in object recognition and found that color effects could be detected in the early components that index visual perceptual processing (including the N1, P2 and N2 components). In addition, they found a color modulation of late visual components associated with semantic processing (N300 and N400). These findings provide evidence that color information is important at both the perceptual and semantic level during object recognition. However, Lu et al. (2010) used color diagnostic objects only, making it difficult to distinguish the potentially different roles of color during the recognition of color and non-color diagnostic objects.

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 P1 and N1 components and the late visual N400 component. The P1 component is an early response to visual stimuli, which peaks at approximately 100 ms following stimulus onset and is best represented over the occipital electrodes. This component has been associated with low-level visual processing but is also sensitive to attention (Mangun & Hillyard, 1991). The P1 is followed by a negative deflection peaking approximately 150 ms after stimulus onset, the N1 component, which has been observed primarily over the occipito-temporal region. The N1 component is an index of perceptual processing: 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). In addition, the P1 and N1 components are sensitive to color effects, including color categorization and early perceptual processes related to categorical color perception (Holmes, Franklin, Clifford, & Davies, 2009). Based on our previous findings, we predicted that the ERP associated with black-and-white, compared to color, stimuli would elicit a more positive P1 and a more negative N1 response over occipital sites for both color and non-color diagnostic objects during object recognition.

Schendan and Kutas (2007a) proposed a *two-state interactive* account for visual object knowledge. First, a system supporting lower-order visual image classification, indexed by the N1 component, is activated. This system is subserved by the posterior ventral cortex, and in the activated state, candidate object models or object parts are retrieved enabling operations such discriminating between faces and other objects. Later, and indexed by the N300 (Barrett & Rugg, 1990; Hamm, Johnson, & Kirk, 2002; McPherson & Holcomb, 1999; Pratarelli, 1994), the occipito-temporal regions are activated again. However, this time to perform higher-order neural computations, involving feedback from other neural systems, such as the prefrontal cortex (Bar et al., 2006). At this stage, detailed visual knowledge, necessary for object model selection, is activated and basic-level categorization is performed (e.g., dog, car, cup; Ganis, Schendan, & Kosslyn, 2007).

The late visual N400 component is related to semantic processing and it is characterized by a negative deflection over central-parietal regions peaking around the 400 ms after stimulus onset. The N400 has been widely used as an index of semantic processing, with an increase in amplitude (i.e., more negative) for semantically unrelated compared to semantically related material (Barrett & Rugg, 1990; Ganis, Kutas, & Sereno, 1996; Hamm, Johnson, & Kirk, 2002; Holcomb & McPherson, 1994; Kutas & Hillyard, 1980a, 1980b; McPherson & Holcomb, 1999; Nigam, Hoffman, & Simons, 1992; Pietrowsky et al., 1996; Pratarelli, 1994; Stuss, Picton, Cerri, Leech, & Stethem, 1992). The N400 effect was initially related to words that are semantically unrelated or unusual in a given semantic sentence context (Kutas and Hillyard 1980a, 1980b), and was first described for pictures by Barrett and Rugg (1990). The authors reported that pictures that were semantically unrelated to a previous prime elicit a more negative ERP around 400 ms after stimuli onset compared to pictures that were semantically related to a previous prime. Given that object color knowledge is represented in the semantic memory of color diagnostic objects, and based on our previous work, we except to find a color effect in the N400 component for this type of objects.

EXPERIMENTAL PROCEDURES

Participants. Twenty 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 color blindness or related color vision problems, 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 are from the same basic category as the Snodgrass and Vanderwart (1980). The objects were divided according to their color diagnosticities into a group of high-color diagnostic objects (31 from the natural categories and 23 from the artifact categories) and into a group of low color diagnostic objects (20 from the natural categories and 34 from the artifact categories). 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 1**).

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 a color replacement tool to select and paste the surface color of color diagnostic objects (**Figure 1**). 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, using Adobe Photoshop CS2. This procedure converts RGB images to grayscale by eliminating the hue and saturation information while retaining the luminance. The luminosity was measured using the histogram information displayed at Adobe Photoshop CS2, which reads the intensity light for each pixel and gives the mean value of the luminosity for each image. We did not find any difference in the luminance values between color diagnostic and non-color diagnostic objects (**Table 1**).

Experimental procedures. The 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 on the computer keyboards 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 (nbs.neuro-bs.com/presentation) was used to display the stimuli on a computer CRT 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 1000 ms. Next, a white screen was presented for 1250 – 1750 ms, followed by the instruction to type the object name. 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 presentation of the stimuli. Before the task, subjects practiced ten 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, Leitner, Kenemans, & van Honk, 2006). Three other electrodes were attached over the right and left mastoids and below the right eye. Vertical eye movements were monitored by the right eye electrode and the Fp2 electrode from the cap, while horizontal eye movements were monitored using the F7 and the F8 electrode from the cap. 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 were analyzed with 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 well as any trials were subjects gave incorrect responses. Data were artifact rejected on a trial-by-trial basis for eyeblink and on a channel-by-channel basis for drift, blocking and excessive alpha wave. In total, 12.3% of the trials were excluded (2.8% incorrect responses; 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 referenced to the mean of the two mastoids. Although a common average reference is considered a reference-independent estimation of scalp voltage (Bertrand, Perrin, & Pernier, 1985), we opted for mastoid reference montage because previous papers that examine color effects on object recognition have mostly been using a mastoid reference (Goffaux et al., 2005; Lu et al., 2010; Proverbio, Burco, Zotto, & Zani, 2004). The 200 ms prior to the stimulus onset served as the baseline for the amplitude measurement for each channel. Trials with correct responses were averaged separately for conditions, synchronous to the onset of the target.

RESULTS

The participants showed high accuracy in 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 ± .05; non-color diagnostic objects: 98.8 ± .02). When the objects were presented in black-and-white, the percentage of correct responses was 96.8% (color diagnostic objects: 94.9 ± .05; non-color diagnostic objects: 98.8 ± .02).

The measured scalp-recordings were analyzed statistically at bilateral pairs of electrodes and for specific time windows. To restrict the number of statistical comparisons, electrodes were selected a priori in regions of interest according to theoretical considerations. To examine the color effects, we compared ERPs elicited by black-and-white with those elicited by color object presentations for each stimulus type in three time windows after stimulus onset: the visual P1 and N1 with a maximum over occipital and parietal regions (from 90 to 110 ms and 130 to 180 ms, respectively), and the N400 (from 350 to 500 ms) with a maximum over the central sites. Mean voltages were computed for each time window and for selected pairs of bilateral electrodes in three scalp regions: centro-parietal (C1/C2, C3/C4, CP1/CP2 and CP3/CP4), parieto-occipital (P5/P6, P7/P8 and PO7/PO8) and occipital (O1/O2). Average waveforms for color diagnostic and non-color diagnostic from occipital and parieto-occipital electrodes can be seen in **Figure 2** and **Figure 3**, respectively. **Figure 4** and **Figure 5** show the average waveforms for color diagnostic and non-color diagnostic from centro-parietal sites, respectively. Responses in the P1 time window was analyzed at occipital sites, while the responses in the N1 time window was analyzed at parieto-occipital sites because early perceptual effects on ERPs were expected in this region (Holmes, Franklin, Clifford, & Davies, 2009; Tanaka, Luu, Weisbrod, & Kiefer, 1999; Wang & Kameda, 2005; Wang & Suemitsu, 2007). The N400 was assessed at centro-parietal electrodes, because N400 response is maximal in this region, when a mastoid references is used (Kutas & Hillyard, 1980a). A four-way (2 x 2 x 2 x 2) repeated-measure ANOVAs was conducted on the mean amplitudes of the P1, N1 and N400 components from representative electrodes. The four factors were presentation order (first *vs.* second presentation), laterality (left *vs.* right), stimulus type (color diagnostic *vs.* non-color diagnostic objects) and color (color *vs.* black-and-white).

Given that there are well documented differences between the ERPs elicited by natural and artifact objects (e.g., Kiefer, 2001; Sitnikova, West, Kuperberg, & Holcomb, 2006) and to avoid misinterpretation of the data and potential confounds between the diagnosticity factor and the semantic category of the objects an additional analysis was carry out considering a subset of stimuli with an equal number of natural and artifact stimuli for the color and non-color diagnostic objects. To conduct this analysis we selected, for each subject, the trials correspondents to a previous randomly selected subset of 20 natural and 20 artifact objects for each stimuli type category: 40 color diagnostic stimuli (20 from the natural category and 20 from the artifact categories) and 40 non-color diagnostic stimuli (20 from the natural category and 20 from the artifact categories). The only statistical difference between color and non-color diagnostic stimuli on the rating variables was the color diagnosticity level ($p > .10$; **Table 2**).

The P1 response. The ANOVA showed a significant effect of color ($F(1, 19) = 9.9$; $p = .005$; $\eta^2 = 0.34$). The black-and-white images (4.4 ± 0.9 μV) were associated with greater positive amplitudes over the occipital sites compared to colored images (3.4 ± 0.8 μV; **Figure 6**). There were no other significant effects or interactions.

When we repeated the analysis with an equal number of natural and artifact objects for the color diagnostic and non-color diagnostic objects we observed the same significant color ($F(1, 19) = 9.5$; $p = .006$; $\eta^2 = 0.33$). The black-and-white images (4.5 ± 0.8 μV) were associated with greater positive amplitudes over the occipital sites compared to colored images (3.5 ± 0.8 μV). There were no other significant effects or interactions.

The N1 response. A significant stimulus type effect ($F(1, 19) = 6.1$; $p = .02$; $\eta^2 = 0.24$) was observed. The non-color diagnostic objects (1.6 ± 0.6 μV) were associated with more negative amplitudes compared to the color diagnostic objects (2.2 ± 0.6 μV) in the N1 time window. A significant effect of color was also found ($F(1, 19) = 17.1$; $p < .001$; $\eta^2 = 0.47$). The typical N1 response was stronger for objects presented in black-and-white compared with color; the black-and-white objects were associated with greater negative amplitudes (1.5 ± 0.6 μV) compared to objects presented in color (2.4 ± 0.6; **Figure 6**). No additional effects or interactions were found.

When the ANOVA was repeated taking into account the subset of stimuli with an equal number of natural and artifact objects for the color diagnostic and non-color diagnostic stimuli the only effect that remained was the color effect ($F(1, 19) = 12.8$; $p = .002$; $\eta^2 = 0.40$). The black-and-white presentations (1.5 ± 0.6 μV) were associated with more negative amplitudes compared to color presentations (2.7 ± 0.6 μV). There were no additional effects or interactions.

The N400 response. A significant color effect (*F*(1, 19) = 8.1; $p = .01$; $\eta^2 = 0.30$) was observed. During the N400 time window, the ERPs associated with black-and-white objects were more negative (6.4 ± 1.3 μV) than the ones associated with the color objects (7.1 ± 1.4 μV). A significant interaction between hemisphere and stimulus type was observed (*F*(1, 19) = 10.3; $p = .005$; $\eta^2 = 0.35$). Planned comparisons showed that on the left hemisphere, the color diagnostic objects (6.4 ± 1.2 μV) elicited more negative amplitudes compared with the non-color diagnostic ones (6.8 ± 1.2 μV; $p = 0.04$); however on the right hemisphere there was no significant differences between the amplitude elicited by color (6.7 ± 1.6 μV) and non-color diagnostic stimuli (6.8 ± 1.6 μV). A significant two-way interaction between stimulus type and color was also observed (*F*(1, 19) = 17.2; $p = .001$; $\eta^2 = 0.48$). Planned comparisons showed that there were no differences in the N400 time window between black-and-white (6.9 ± 1.3 μV) and color (6.5 ± 1.4 μV; $p = .3$) 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 (5.9 ± 1.4 μV) compared to color presentations (7.7 ± 1.4 μV; $p < .001$). Therefore, when objects are strongly associated with a color, the N400 response is more negative for black-and-white objects compared to color objects (**Figure 6**). No additional effects or interactions were significant.

We observed the same color effect as in the previous analysis when the ANOVA was repeated considering a subset of stimuli with an equal number of natural and artifact objects for the color diagnostic and non-color diagnostic categories (*F*(1, 19) = 12.5; $p = .002$; $\eta^2 = 0.40$). Black-and-white presentations (6.0 ± 1.4 μV) were associated with more negative amplitudes compared to color (7.0 ± 1.4 μV) presentations in the N400 time window. The significant interaction between stimulus type and color was also observed in this analysis (*F*(1, 19) = 11.9; $p = .003$; $\eta^2 =$

0.39). For the color diagnostic objects, the typical N400 response was stronger for black-and-white presentations (5.5 ± 1.4 μV) compared with color presentations (7.4 ± 1.4 μV; *p* < .001). However, for the non-color diagnostic objects the amplitude between black-and-white (6.5 ± 1.5 μV) and color presentations was not statistical significant in the N400 time window (6.5 ± 1.4 μV; *p* = .8) in the N400 time window. There were no other significant effects or interactions.

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 naming 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.

For both color diagnostic and non-color diagnostic objects, we observed color effects in the early components (N1 and P1). These components reflect early perceptual processes and are found to be sensitive to variations in the physical stimulus characteristics, but have also been shown to be modulated by attention (Mangun & Hillyard, 1991; Vogel & Luck, 2000). Our results showed that the black-and-white object presentations elicited a greater positive response in the P1 time-window and a greater negative response in the N1 time-window compared to the color presentations. This suggests that when objects are presented in color, there are lower demands on early perceptual processing. This finding suggests that color facilitates shape segmentation, like grouping object parts on the basis of proximity and similarity principles. Actually, it has been showed that perceptual grouping processes takes place at the early stages of the visual processing related to forming perceptual units for object recognition (Bruce, Green, & Georgeson, 2003). In addition, ERP studies have reported that these grouping processes are associated with modulations of the P1 and N1 components (Han, 2004; Han, Ding, & Song, 2002; Han, Song, Ding, Yund, & Woods, 2001). Such early grouping effects have been localized to the calcarie cortex (Han, Jiang, Mao, Humphrey, & Qin, 2005). However, perceptual grouping operations have also been described in later ERP components (Casco, Campana, Han, & Guzzon, 2009; Han & Humphrey, 2007; Han, Jiang, Mao, Humphrey, & Qin, 2005; Schendan & Kutas, 2007b). For instance, Schedan and Kutas (2007) observed an occipitotemporoparietal P2 repetition effect when similar perceptual grouping processes of good continuation and closure were repeatedly engaged between the study and the test experiment. Most likely, the perceptual processes occurring in the P200 time window are already under the influence of visual object knowledge that directs the attention to salient image features (Schendan & Kutas, 2007b) and reflects the feedback from high-level brain structures (Han & Humphrey, 2007; Han, Jiang, Mao, Humphrey, & Qin, 2005).

The color effects found in the P1 and N1 components are unlikely to be related to differences in the low-level visual properties of the stimuli (e.g., luminance, contrast), because the color stimuli were converted into black-and-white in such a way that the luminance was kept constant; moreover, the luminance values between color diagnostic and non-color diagnostic stimuli were not statistically significant. However, and since there is a difference between physically isoluminance and psychological isoluminance we divided the objects into “light and dark”, based upon the luminance values, and we compared the light colored *vs.* the dark black-and-white and the dark colored *vs.* the light black-and-white in the left and right representative sites in the P1 and N1 time windows. In the P1 time window it was possible to observed that the black-and-white stimuli were always associated with more positive amplitudes compared to color stimuli ($Z > 2.4$; $p < .01$), while in the N1 time window the black-and-white stimuli were always associated with more negative amplitudes compared to color stimuli ($Z > 2.2$; $p < .02$). Thus, our results provide a clear demonstration of color effects on early perceptual components (P1 and N1), which are independent of the color diagnosticity status of the objects, and these cannot be explained in term of perceptual luminance differences. Color effects in the early components have been found for color diagnostic objects (Lu et al., 2010) and natural diagnostic scenes (Goffaux et al., 2005). Our work extends these findings by showing that the color effects in the N1 component are independent of the diagnosticity status. This suggests that color modulates the early visual perceptual stages for both color diagnostic and non-color diagnostic objects and most likely contributes to shape segmentation processes.

In addition, we found a color effect for color-diagnostic objects in the N400 component. The N400 component is an index of semantic processing that reflects general object knowledge sensitive to information extracted after the initial categorization (Hamm, Johnson, & Kirk, 2002; McPherson & Holcomb, 1999). Black-and-white stimuli elicited a greater negative N400 response over the central-parietal region compared to the color stimuli, suggesting that surface color is processed at the semantic level for the color diagnostic objects. Therefore, the presence of surface color might activate a more extensive semantic network, facilitating object recognition and naming. It is important to note that we used the same set of shapes and objects, counterbalanced across the color and black-and-white conditions, and therefore the observed ERP effects can only be attributed to the nature of the color-shape associations and not to any other sensory or physical stimulus characteristic. Lu and collaborators (2010) also found a N400 color effect with the congruent color condition eliciting more positive amplitudes compared with the black-and-white condition in this time window. However, the authors did not report any differences in this time window between congruent (e.g., red apple) and incongruent conditions (e.g., red apple), suggesting that the activation of color is complete in this time window (Lu et al., 2010). The authors proposed that object color knowledge is activated during the time window of the N300 component, which is a negative deflection that occurs in the frontal sites previously to the negative N400 deflecting occurring in the centro-parietal sites. The N300 component marks the first ERP divergence related to object categorization, showing a smaller amplitude for correctly categorized objects (McPherson & Holcomb, 1999; Schendan & Kutas, 2002). The N300 also shows effects related to typicality, with a smaller amplitude for canonical views compared to uncommon, non-canonical views (Schendan & Kutas, 2003). 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 also found a similar result: atypically colored objects generated a more negative N300 component than typically colored objects on the frontal sites, suggesting that the typical color presentation is better recognized and categorized than the atypical color presentation (Bramão et al., 2012). In the present study, we did not analyze the color effects in this time window because we did not find a clear N300 component in our ERPs waves. It is important to notice 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 clear N300 component.

In summary, our ERP results confirm that surface color is processed at different levels of the visual hierarchy during object recognition. 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 perceptual stages for non-color diagnostic objects. For the recognition of color and non-color diagnostic objects, color information was found to be an important cue for the initial image segmentation, lowering the initial demand on the visual system. However, and beyond the facilitation that color information confers to the initial visual stages, our results showed a color effect in the later stages of object recognition for color diagnostic objects. At the later visual processing stages, color information might trigger the selection of the structural object description from long-term visual memory, which is matched to the perceptual input (Bramão et al., 2012). Additionally, the N400 color effect observed in this study suggests that color information might activate a more extensive object semantic network. When we see an object, color and shape are likely to be processed in parallel, in an interactive fashion. Some studies indicate that the same neural circuits, in early visual cortical regions, processes information about color, shape and luminance (Gegenfurtner, 2003). At some point, this information must be combined to achieve a unitary representation of the visual world. One possibility is that this information is combined during the structural description selection stage, where color act as a cue to limit the range of candidate structural descriptions. In a recent meta-analysis (Bramão, Reis, Petersson, & Faísca, 2011), we also found a significant difference between the color effects observed in studies that used color diagnostic objects and studies that used non-color diagnostic objects. Studies that used color diagnostic objects were found to have a strong effect of color; compared to the studies that used non-color diagnostic objects, for which only a marginally significant effect of color information was observed. Previous research has established a role for color in the early and late stages of object recognition; however, these studies either did not control for the color diagnosticity status of the objects or only used high-color diagnostic objects (Davidoff, 1991; Davidoff, Walsh, & Wagemans, 1997; Gegenfurtner & Rieger, 2000; Goffaux et al., 2005; Lu et al., 2010; Proverbio, Burco, Zotto, & Zani, 2004; Wurm, Legge, Isenberg, & Luebker, 1993). For example, Davidoff (1991) proposed a model of object recognition in which color participates in object recognition at the later stages of the visual processing (i.e., after the structural object model has been accessed). In contrast, Price and Humphreys (1989) argued that color is processed at the early visual stages, and that there are separate representations for color and shape, but that these representations are richly interconnected. Thus, color objects can activate color representations that in turn activate associated shape representations (Humphreys et al., 1994; Price and Humphreys, 1989).

In conclusion, the data presented in this work shows that the role of color in object recognition is dependent of the association strength between color and shape. When the correlation between color and shape is high, as in the case of the color diagnostic objects, color information is important at the semantic level, whereas when this correlation is low, as it is in the case of the non-color diagnostic objects, then color improves object recognition only at the early stages of visual processing.

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FIGURE LEGENDS

Figure 1. Examples of color and non-color diagnostic pictures used in the experiment.

Figure 2. Average ERP waveforms from occipital and parieto-occipital representative electrodes for color diagnostic objects presented in color (solid line) and in black-and-white (dotted line).

Figure 3. Average ERP waveforms from occipital and parieto-occipital representative electrodes for non-color diagnostic objects presented in color (solid line) and in black-and-white (dotted line).

Figure 4. Average ERP waveforms from centro-parietal representative electrodes for color diagnostic objects presented in color (solid line) and in black-and-white (dotted line).

Figure 5. Average ERP waveforms from centro-parietal representative electrodes for non-color diagnostic objects presented in color (solid line) and in black-and-white (dotted line).

Figure 6. Topographic distribution of the black-and-white *vs.* color objects in the time windows of interest for the color diagnostic and non-color diagnostic objects.

TABLES

Table 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 (.2)	2.2 (.7)	Z = 8.2, $p < .001$
Luminosity	228.5 (13.5)	227.6 (13.4)	Z = .1, $p = .9$
Prototypicality	4.3 (.5)	4.3 (.3)	Z = .8, $p = .4$
Familiarity	4.3 (.5)	4.3 (.5)	Z = -.1, $p = .9$
Visual ambiguity	2.4 (.8)	2.2 (.7)	Z = .8, $p = .4$
Visual complexity	2.6 (.7)	2.7 (.6)	Z = -.3, $p = .8$

Table 2. Mean (SD) ratings for color diagnosticity, prototypicality, familiarity, visual ambiguity and visual complexity for the subset of color diagnostic and non-color diagnostic objects with an equal number of objects from the natural and from the artifact categories.

	Color Diagnostic Objects	Non-Color Diagnostic Objects	Mann-Whitney U Test
Color Diagnosticity	4.4 (.3)	2.3 (.7)	Z = 7.7, $p < .001$
Luminosity	227.6 (13.6)	227.4 (13.2)	Z = .04, $p = .9$
Prototypicality	4.3 (.5)	4.3 (.4)	Z = .1, $p = .4$
Familiarity	4.3 (.5)	4.3 (.5)	Z = .9, $p = .9$
Visual ambiguity	2.3 (.7)	2.4 (.7)	Z = -.3, $p = .7$
Visual complexity	2.6 (.7)	2.8 (.6)	Z = -1.1, $p = .2$