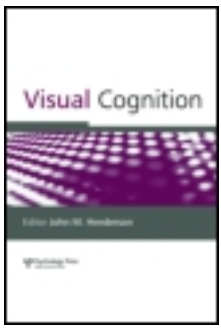

Visual Cognition
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pvis20

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Version of record first published: 05 Nov 2012.

To cite this article: Inês Bramão, Ana Francisco, Filomena Inácio, Luís Faísca, Alexandra Reis & Karl Magnus Petersson (2012): Electrophysiological evidence for colour effects on the naming of colour diagnostic and noncolour diagnostic objects, Visual Cognition, DOI:10.1080/13506285.2012.739215

To link to this article: http://dx.doi.org/10.1080/13506285.2012.739215

VISUAL COGNITION, 2012, iFirst, 1–22

Psychology Press
Taylor & Francis Group

Electrophysiological evidence for colour effects on the naming of colour diagnostic and noncolour diagnostic objects

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In this study, we investigated the level of visual processing at which surface colour information improves the naming of colour diagnostic and noncolour diagnostic objects. Continuous electroencephalograms were recorded while participants performed a visual object naming task in which coloured and black-and-white versions of both types of objects were presented. The black-and-white and the colour presentations were compared in two groups of event-related potentials (ERPs): (1) The P1 and N1 components, indexing early visual processing; and (2) the N300 and N400 components, which index late visual processing. A colour effect was observed in the P1 and N1 components, for both colour and noncolour diagnostic objects. In addition, for colour diagnostic objects, a colour effect was observed in the N400 component. These results suggest that colour information is important for the naming of colour and noncolour diagnostic objects at different

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This work was supported by Fundação para a Ciência e Tecnologia (REEQ/879/PSI/2005; PTDC/PSI-PCO/110734/2009, IBB/CBME, LA, FEDER/POCI 2010), Max Planck Institute for Psycholinguistics, Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, Vetenskapsrådet (8276), Hedlunds Stiftelse and Stockholm County Council (ALF, FoUU). Inês Bramão was supported by a PhD fellowship (FCT/SFRH/BD/27381/2006).

http://www.psypress.com/viscog http://dx.doi.org/10.1080/13506285.2012.739215

levels of visual processing. It thus appears that the visual system uses colour information, during naming of both object types, at early visual stages; however, for the colour diagnostic objects naming, colour information is also recruited during the late visual processing stages.

Keywords: Colour diagnosticity; Colour information; Object naming; Perceptual processing; Semantic processing.

There is a large body of research suggesting that colour information plays a role in object identification (for a review, see Tanaka, Weiskopf, & Williams, 2001). However, the processing stages at which this occurs and the types of objects that might be more efficiently identified by colour processing are both matters of debate. Attempts to address this issue have primarily focused on colour diagnosticity, which refers to the degree to which a particular object is associated with a specific colour (Tanaka & Presnell, 1999). For example, a *strawberry*—a colour diagnostic object—is strongly associated with the colour *red*, whereas a *comb*—a noncolour diagnostic object—is not associated with any specific colour. some results suggest that colour information improves object naming and identification independent of colour diagnosticity (Rossion & Pourtois, 2004; Uttl, Graf, & Santacruz, 2006), whereas other results indicate that colour only improves the naming and identification of colour diagnostic objects (Nagai & Yokosawa, 2003; Tanaka & Presnell, 1999).

In a previous behavioural study, we reported results which suggest that colour modulates the identification of colour and noncolour diagnostic objects at different levels of visual processing: For colour diagnostic objects, colour plays an important role at the semantic level, whereas for noncolour diagnostic objects, colour plays a role at a presemantic recognition level (Bramão, Inácio, Faísca, Reis, & Petersson, 2011). In this study, we built on these results in an electroencephalogram (EEG) experiment. Unlike behavioural measures, event-related potentials (ERPs) allow for the analysis of electrophysiological signatures of cognitive processes with high temporal resolution at the millisecond timescale. This represents an optimal approach to investigate the level of visual processing at which surface colour modulates object identification. For example, in a recent ERP study, Lu et al. (2010) investigated the impact of colour in object categorization and found that colour 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 colour modulation of late visual components associated with semantic processing (N300 and N400). These findings provide evidence that colour information is important at both the perceptual and semantic level during object recognition. However, Lu et al. (2010) used colour diagnostic objects only, making it difficult to distinguish

the potentially different roles of colour during the recognition of colour and noncolour diagnostic objects.

In this study, we recorded ERPs during a visual naming task in which coloured and black-and-white versions of colour and noncolour diagnostic objects were presented. The differences between colour and black-and-white presentations were investigated with respect to the early visual P1 and N1 components and the late visual N300 and N400 components. 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 occipitotemporal 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 colour effects, including colour categorization and early perceptual processes related to categorical colour perception (Holmes, Franklin, Clifford, & Davies, 2009). Based on our previous findings, we predicted that the ERP associated with black-and-white, compared to colour stimuli would elicit a more positive P1 and a more negative N1 response over occipital sites for both colour and noncolour diagnostic objects during object naming.

The late visual N300 and N400 components are ERPs related to semantic processing. N300 is a negative ongoing component that peaks at approximately 300 ms after stimulus presentation and has an anterior topographic distribution (Barrett & Rugg, 1990; McPherson & Holcomb, 1999; Pratarelli, 1994). The N300 appears to be specific for visual stimuli and reflects neural processes related to object model selection and generic memory. The N300 is the first marker of successful object categorization, with an increased amplitude (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, 2007a). Schendan and Kutas (2007a) proposed a two-state interactive account of visual object knowledge in which the cognitive neuroscience research concerning the N300 and N1 effects are integrated. 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, the occipitotemporal regions are activated again, but this time to perform higher order neural computations,

involving feedback from other neural systems, such as the prefrontal cortex (Schendan & Maher, 2009). 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).

In a previous electrophysiological study, using a colour verification task with high colour diagnostic objects, we found a strong colour effect on the N300 time window—atypical colour objects presentations elicited a more negative ERP over the frontal sites compared to typical colour objects. This result suggests that surface colour is an important cue that facilitates the selection of a stored object representation from long-term memory (Bramão et al., 2012). In this study we also expect to find a N300 colour effect for the colour diagnostic objects corroborating this previous finding. We predict a more negative N300 for black-and-white presentations compared to colour presentations for the colour diagnostic objects. We do not expect to find a colour effect in the N300 time window for the noncolour diagnostic objects, because these objects are not strongly associated with any particular colour.

The N300 is followed by the N400 component, which is a negative deflection over central-parietal regions peaking at approximately 400 ms after stimulus onset. The N400 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 et al., 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 & 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 colour knowledge is represented in the semantic memory of colour diagnostic objects, we expect to find a colour effect in the N400 component for these objects and not for the noncolour diagnostic objects, with the black-and-white object presentations being associated with a more negative N400 over the centroparietal sites compared to colour presentations.

EXPERIMENTAL PROCEDURES

Participants

Twenty right-handed native Portuguese speakers (mean age [$\pm SD$] = 24 $\pm$ 4 years, range 18–33 years; mean years of education [$\pm SD$] = 15 $\pm$ 1 years,

range 13–17 years; five 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 colour blindness or related colour 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, Faísca, Ingvar, and 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 colour diagnosticity. Each stimulus was presented for 1 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 nonambiguous 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 colour diagnosticity was defined as "the degree to which the object is associated with a specific colour", and was rated on a 5-point scale (1 = low colour diagnostic, 5 = a high colour 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 those in Snodgrass and Vanderwart (1980). The objects were divided according to their colour diagnosticities into a group of high-colour diagnostic objects (31 from the natural categories and 23 from the artifact categories) and into a group of low colour diagnostic objects (20 from the natural categories and 34 from the artifact categories). Colour diagnosticity was the only difference between the two groups of objects that reached statistical significance. The mean comparisons between colour diagnostic and noncolour diagnostic items on the other rating variables were not significant ($p > .10$; Table 1).

To ensure that the colour and noncolour diagnostic objects were matched for colour frequency and luminance, we created the colour version of noncolour diagnostic pictures by using the surface colour of the colour diagnostic pictures (Figure 1). First, we selected the surface colour of the colour diagnostic objects by averaging the RGB values of each image pixel. The selected RGB colour values were then paste onto the surface of the noncolour diagnostic objects by using the replacement colour tool in Adobe Photoshop CS2. This procedure allows the replacement of any colour on a picture without losing any detail. The luminance of the colour-replaced (noncolour diagnostic) picture was adjusted using the brightness tool in Adobe Photoshop CS2. To create the black-and-white versions, the coloured pictures of both object types were converted into greyscale, also using Adobe Photoshop CS2. This procedure converts RGB images to greyscale 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 colour diagnostic and noncolour diagnostic objects.

TABLE 1
Mean (*SD*) ratings for colour diagnosticity, prototypicality, familiarity, visual ambiguity, and visual complexity for colour diagnostic and noncolour diagnostic objects

	Colour diagnostic objects	*Noncolour diagnostic objects*	*Mann-Whitney U-test*
Colour diagnosticity	4.4 (0.2)	2.2 (0.7)	$Z = 8.2$, $p < .001$
Luminosity	228.5 (13.5)	227.6 (13.4)	$Z = 0.1$, $p = .9$
Prototypicality	4.3 (0.5)	4.3 (0.3)	$Z = 0.8$, $p = .4$
Familiarity	4.3 (0.5)	4.3 (0.5)	$Z = -0.1$, $p = .9$
Visual ambiguity	2.4 (0.8)	2.2 (0.7)	$Z = 0.8$, $p = .4$
Visual complexity	2.6 (0.7)	2.7 (0.6)	$Z = -0.3$, $p = .8$

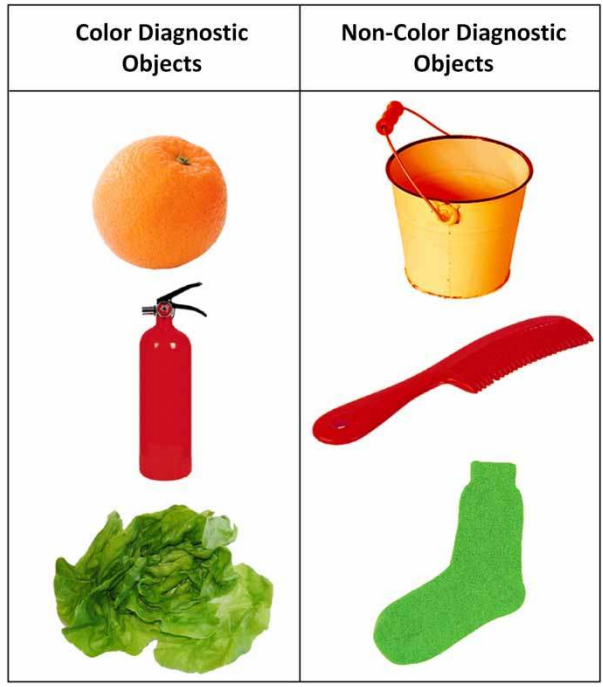

Figure 1. Examples of colour and noncolour diagnostic pictures used in the experiment. To view this figure in colour, please see the online issue of the Journal.

Experimental procedures

The objects were presented in a randomized order to each subject. Each object was presented twice, in colour and in black-and-white, comprising a total of 216 trials. Half of the subjects saw the coloured version of a particular object first, and 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 inch; spatial resolution: 1024×768; colour resolution: 24 bits) and to register the participants' responses. Each trial started with a fixation cross (+) presented at the centre of the screen for 1250 ms. The fixation cross was followed by presentation of the object picture (500×362 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 centre of the screen and to avoid eye blinks and body movements during the presentation of the stimuli. Before the task, subjects practised 10 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 and located at standard left and right hemispheric positions over the frontal, parietal, occipital, and temporal areas (Figure 2). 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, and horizontal eye movements were monitored using the F7 and the F8 electrode from the cap. Bioelectrical signals were amplified using an ActiveTwo Biosemi amplifier

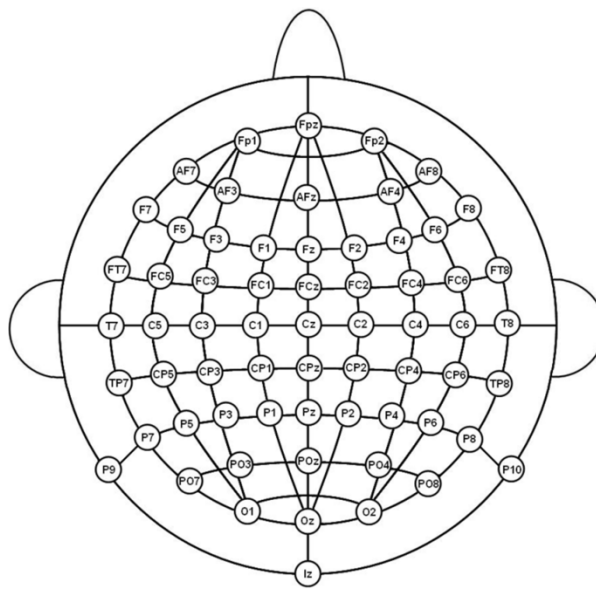

Figure 2. The 64 channel electrode montage used for EEG recording.

(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 analysed 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 timelocked 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 where subjects gave incorrect responses. Data were visually 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 colour 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 colour, subjects gave the correct response 97.6% of the time (colour diagnostic objects: 96.5 ± 0.05; noncolour diagnostic objects: 98.8 ± 0.02). When the objects were presented in black-and-white, the percentage of correct responses was 96.8% (colour diagnostic objects: 94.9 ± 0.05; noncolour diagnostic objects: 98.8 ± 0.02).

The measured scalp-recordings were analysed 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 colour effects, we compared ERPs elicited by black-and-white with those elicited by colour object presentations for each stimulus type in four time windows after stimulus onset: The visual P1 and N1 with a maximum over occipital and parietal regions (from 90 to 110 ms and from 130 to 180 ms, respectively), and the late

N300 and N400 with a maximum over frontal and central sites (from 200 to 350 ms and from 350 to 500 ms, respectively). Mean voltages were computed for each time window and for selected pairs of bilateral electrodes in four scalp regions: Frontal (AF3/AF4, F3/F4), centroparietal (C1/C2, C3/C4, CP1/CP2, and CP3/CP4), parietooccipital (P5/P6, P7/P8, and PO7/PO8), and occipital (O1/O2). Responses in the P1 time window were analysed at occipital sites, and the responses in the N1 time window were analysed at parietooccipital sites because early perceptual effects on ERPs were expected in this region (Holmes et al., 2009; Tanaka et al., 1999; Wang & Kameda, 2005; Wang & Suemitsu, 2007). The colour effects on the N300 were assed at frontal electrodes, and the N400 was assessed at centroparietal electrodes, because responses are maximal in these regions, when a mastoid reference is used (Kiefer, 2001; Kutas & Hillyard, 1980a). A four-way ($2 \times 2 \times 2 \times 2$) repeated-measure ANOVA was conducted on the mean amplitudes of the P1, N1, N300, and N400 components from the representative electrodes. The four factors were presentation order (first vs. second presentation), laterality (left vs. right), stimulus type (colour diagnostic vs. noncolour diagnostic objects), and colour (colour 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 carried out considering a subset of stimuli with an equal number of natural and artifact objects for the colour and noncolour diagnostic conditions. To conduct this analysis we selected, for each subject, the trials correspondents to a randomly selected subset of 20 natural and 20 artifact objects from each stimuli type: 40 colour diagnostic stimuli (20 from the natural category and 20 from the artifact categories) and 40 noncolour diagnostic stimuli (20 from the natural category and 20 from the artifact categories). The only statistical difference between colour and noncolour diagnostic stimuli on the rating variables was the colour diagnosticity level ($p > .10$; Table 2). Average waveforms at representative electrodes for colour diagnostic and noncolour diagnostic objects, considering this subset of data, can be seen in Figures 3 and 4, respectively.

The P1 response

The ANOVA showed a significant effect of colour, $F(1, 19) = 9.9$, $p = .005$, $\eta^2 = .34$. The black-and-white images (4.4 ± 0.9 μV) were associated with greater positive amplitudes over the occipital sites compared to coloured images (3.4 ± 0.8 μV). There were no other significant effects or interactions.

When we repeated the analysis with an equal number of natural and artifact objects for the colour diagnostic and noncolour diagnostic objects

TABLE 2
Mean (*SD*) ratings for colour diagnosticity, prototypicality, familiarity, visual ambiguity, and visual complexity for the subset of colour diagnostic and noncolour diagnostic objects with an equal number of objects from the natural and from the artifact categories

	Colour diagnostic objects	*Noncolour diagnostic objects*	*Mann-Whitney U-test*
Colour diagnosticity	4.4 (0.3)	2.3 (0.7)	$Z = 7.7$, $p < .001$
Luminosity	227.6 (13.6)	227.4 (13.2)	$Z = 0.04$, $p = .9$
Prototypicality	4.3 (0.5)	4.3 (0.4)	$Z = 0.1$, $p = .4$
Familiarity	4.3 (0.5)	4.3 (0.5)	$Z = 0.9$, $p = .9$
Visual ambiguity	2.3 (0.7)	2.4 (0.7)	$Z = -0.3$, $p = .7$
Visual complexity	2.6 (0.7)	2.8 (0.6)	$Z = -1.1$, $p = .2$

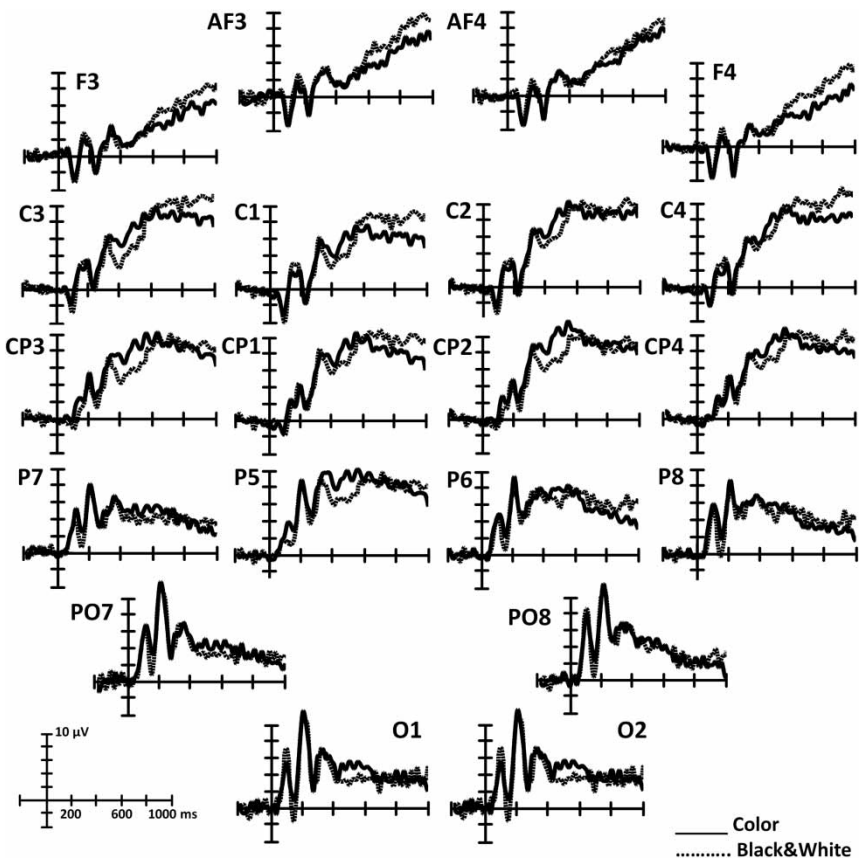

Figure 3. Average ERP waveforms from representative electrodes for colour diagnostic objects presented in colour (solid line) and in black-and-white (dotted line).

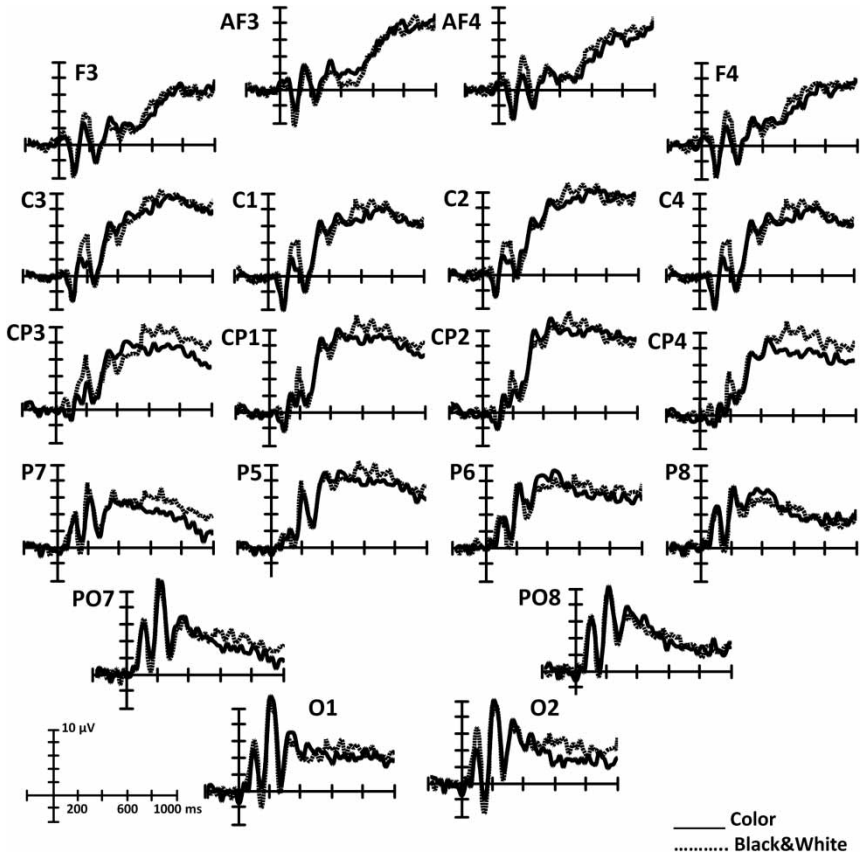

Figure 4. Average ERP waveforms from representative electrodes for noncolour diagnostic objects presented in colour (solid line) and in black-and-white (dotted line).

we observed the same significant colour effect, $F(1, 19) = 9.5$, $p = .006$, $\eta^2 = .33$. The black-and-white images (4.5 ± 0.8 µV) were associated with greater positive amplitudes over the occipital sites compared to coloured images (3.5 ± 0.8 µV; Figure 5). There were no other significant effects or interactions.

The N1 response

A significant stimulus type effect, $F(1, 19) = 6.1$, $p = .02$, $\eta^2 = .24$, was observed. The noncolour diagnostic objects (1.6 ± 0.6 µV) were associated with more negative amplitudes compared to the colour diagnostic ones (2.2 ± 0.6 µV) in the N1 time window. A significant effect of colour was also found, $F(1, 19) = 17.1$, $p < .001$, $\eta^2 = .47$. The typical N1 response was

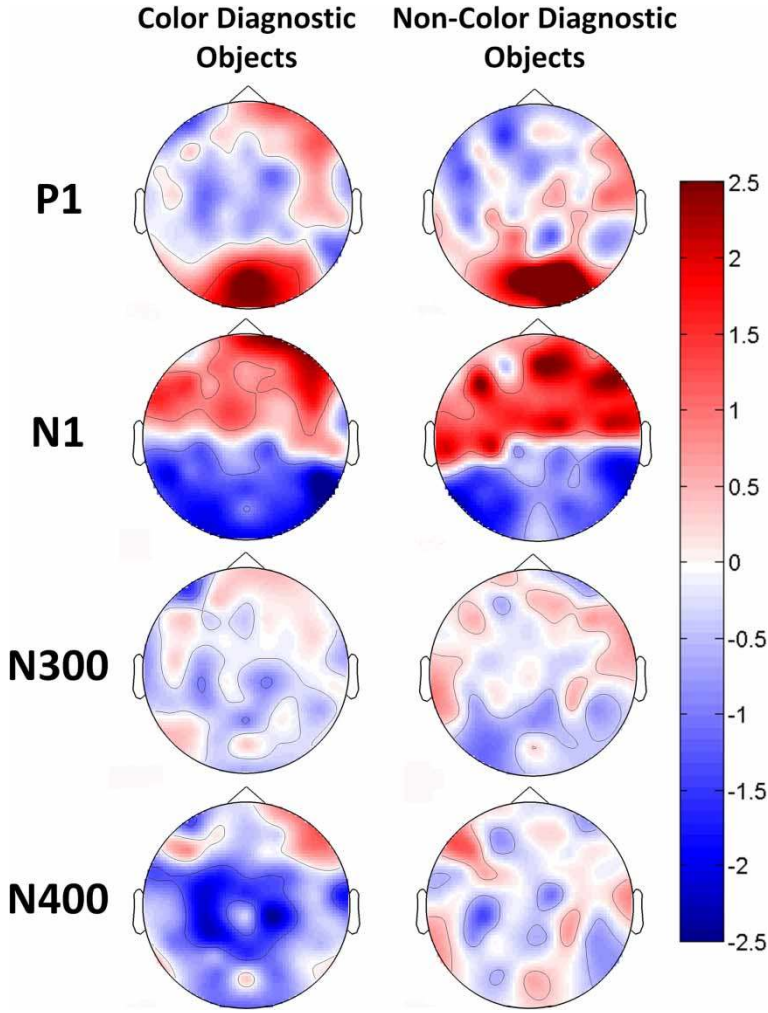

Figure 5. Topographic distribution of the black-and-white versus colour objects in the time windows of interest for the colour diagnostic and noncolour diagnostic objects. The difference voltage maps were computed by subtracting the average ERPs colour from the average ERPs black-and-white presentations. Positive differences are shown is red, negative differences are shown in blue, and the zero means that there is no difference. To view this figure in colour, please see the online issue of the Journal.

stronger for objects presented in black-and-white compared with colour; the black-and-white objects were associated with greater negative amplitudes (1.5 ± 0.6 μV) compared to objects presented in colour (2.4 ± 0.6). 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 colour diagnostic and noncolour diagnostic stimuli, the only effect that remained was the colour effect, $F(1, 19) = 12.8$, $p = .002$, $\eta^2 = .40$. The black-and-white presentations (1.5 ± 0.6 μV) were associated with more negative amplitudes compared to colour presentations (2.7 ± 0.6 μV; Figure 5). There were no additional effects or interactions.

The N300 response

A marginal effect of colour was observed, $F(1, 19) = 3.4$, $p = .08$, $\eta^2 = .42$, was observed. During this time window, the ERPs associated with black-and-white objects were more positive (1.3 ± 1.2 μV) than the ones associated with the black-and-white objects (0.8 ± 1.3 μV).

When we repeated the analysis with an equal number of natural and artifact objects for the colour diagnostic and noncolour diagnostic objects no significant effects or interactions were found (Figure 5).

The N400 response

A significant colour effect, $F(1, 19) = 8.1$, $p = .01$, $\eta^2 = .30$, 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 colour objects (7.1 ± 1.4 μV). A significant interaction between hemisphere and stimulus type was observed, $F(1, 19) = 10.3$, $p = .005$, $\eta^2 = .35$. Planned comparisons showed that on the left hemisphere, the colour diagnostic objects (6.4 ± 1.2 μV) elicited more negative amplitudes compared with the noncolour diagnostic ones (6.8 ± 1.2 μV; $p = .04$); however, on the right hemisphere there was no significant differences between the amplitude elicited by colour (6.7 ± 1.6 μV) and noncolour diagnostic stimuli (6.8 ± 1.6 μV). A significant two-way interaction between stimulus type and colour was also observed, $F(1, 19) = 17.2$, $p = .001$, $\eta^2 = .48$. Planned comparisons showed that there were no differences in the N400 time window between black-and-white (6.9 ± 1.3 μV) and colour (6.5 ± 1.4 μV; $p = .3$) presentations for the noncolour diagnostic objects. However, colour 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 colour presentations (7.7 ± 1.4 μV; $p < .001$). Therefore, when objects are strongly associated with a colour, the N400 response is more negative for black-and-white objects compared to colour objects. No additional effects or interactions were significant.

We observed the same colour 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 colour diagnostic and noncolour diagnostic categories, $F(1, 19) = 12.5$, $p = .002$, $\eta^2 = .40$. Black-and-white presentations (6.0 ± 1.4 μV) were associated with more negative amplitudes compared to colour (7.0 ± 1.4 μV) presentations in the N400 time window. The significant interaction between stimulus type and colour was also observed in this analysis, $F(1, 19) = 11.9$, $p = .003$, $\eta^2 = .39$. For the colour diagnostic objects, the typical N400 response was stronger for black-and-white presentations (5.5 ± 1.4 μV) compared with colour presentations (7.4 ± 1.4 μV; $p < .001$). However, for the noncolour diagnostic objects the amplitude between black-and-white (6.5 ± 1.5 μV) and colour presentations was not statistical significant in the N400 time window (6.5 ± 1.4 μV; $p = .8$; Figure 5). There were no other significant effects or interactions.

DISCUSSION

In this study, we examined the visual processing level at which colour information participates in the naming of colour diagnostic and noncolour diagnostic objects. ERPs were recorded during an object naming task, in which subjects were asked to identify and name colour diagnostic and noncolour diagnostic objects presented in both colour and black-and-white. For reasons of clarity, and to avoid misinterpretation of the data, we focus our discussion on the results observed in the analysis, considering an equal number of natural and artifact objects for the colour and noncolour diagnostic objects.

For both colour diagnostic and noncolour diagnostic objects, we observed colour 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 colour presentations. This might indicate that, when objects are presented in colour, there are lower demands on early perceptual processing. Colour might facilitate shape segmentation operations, 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 in 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 et al., 2005; Schendan & Kutas, 2007b). For instance, Schedan and Kutas (2007b) 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 et al., 2005).

The colour 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 colour stimuli were converted into black-and-white in such a way that the luminance was kept constant; moreover, the luminance values between colour diagnostic and noncolour 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 coloured versus the dark black-and-white and the dark coloured versus 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 observe that the black-and-white stimuli were always associated with more positive amplitudes compared to colour stimuli, $Z > 2.4$, $p < .01$, whereas in the N1 time window the black-and-white stimuli were always associated with more negative amplitudes compared to colour stimuli, $Z > 2.2$, $p < .02$. Thus, our results provide a clear demonstration of colour effects on early perceptual components (P1 and N1), which are independent of the colour diagnosticity status of the objects, and cannot be explained in term of perceptual luminance differences. Colour effects in the early components have been found for colour diagnostic objects (Lu et al., 2010) and natural diagnostic scenes (Goffaux et al., 2005). Our work extends these findings by showing that the colour effects in the N1 component are independent of the diagnosticity status. This suggests that colour modulates the early visual perceptual stages for both colour and noncolour diagnostic objects and most likely contributes to shape segmentation processes.

However, we cannot exclude the possibility that the colour effect observed in the early visual ERPs results from different brain activity responses to colour and to black-and-white stimuli, indicating that colour and black-and-white stimuli are being processed in different channels. Electrophysiological recordings exploring the time course of colour processing have found separated source activity to colour stimulation which starts at approximately

100 ms after stimuli onset and peaks around 140 ms in the region of V4—a region located in the inferior surface of the occipital lobe in the region of the lingual and fusiform gyrus, known as the human colour centre (Allison et al., 1993; Buchner, Weyer, Frackowiak, Romaya, & Zeki, 1994). However, there is no agreement in the literature concerning the fact that V4 is a specialized cerebral brain region for colour processing (for a review, Roe et al., 2012). Electrophysiological studies with both humans (Plendl et al., 1993) and monkeys (Kulikowski, Walsh, McKeefry, Butler, & Carden, 1994) have found that the responses in V4 region to black-and-white stimuli are indistinguishable from responses to colour stimuli, supporting the evidence that the cells in V4 are not exclusively concerned with colour. Moreover, some more recent data indicate that the same neural circuits, in early visual cortical regions, process information about colour, shape, and luminance (Gegenfurtner, 2003).

Surprisingly, we did not observe a colour effect in the N300 time window. 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, noncanonical views (Schendan & Kutas, 2007a). Based on this, we expected that black-and-white presentations of colour diagnostic objects would be more negative than colour presentation in this time window (i.e., objects presented in colour are more easily recognized than those presented in black-and-white). Other studies have found colour effects in this time window. For example, Lu et al. (2010) found that black-and-white and atypically coloured objects were associated with more negative amplitudes in this time window compared with typical colour objects, suggesting that object colour knowledge is activated during the time window of the N300 component. In a previous colour knowledge verification study, we found a similar result: Atypically coloured objects generated a more negative N300 component than typically coloured objects, suggesting that colour is an important cue for the selection of the structural description form stored in the long-term memory (Bramão et al., 2012). In the present study, we did not replicate these findings, and this apparent discrepancy is most likely task related. In this context, 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 colour effect on the N300 time window. Another possibility is that black-and-white objects are more easily recognized or identified than colour objects. However, we used the same object set in a previous behavioural study and found that colour object presentations are named and categorized faster than the black-and-white versions of the same object (Bramão, Inácio, et al., 2011).

In addition, we found a colour effect for colour 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 et al., 2002; McPherson & Holcomb, 1999). Black-and-white stimuli elicited a greater negative N400 response over the central-parietal region compared to the colour stimuli, suggesting that surface colour is processed at the semantic level for the colour diagnostic objects. Therefore, the presence of surface colour 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 colour and black-and-white conditions, and therefore the observed ERP effects can only be attributed to the nature of the colour–shape associations and not to any other sensory or physical stimulus characteristic. It is also important to notice that, besides the fact that each object was repeated twice in the naming task (black-and-white and colour presentation), no repetition effects or interactions were found in the data analysis, which excludes any potential confound between colour and repetition order.

In summary, our ERP results confirm that surface colour is processed at different levels of the visual hierarchy during object naming and identification. It appears that surface colour is processed both at early visual perceptual and at later visual semantic stages during colour diagnostic object identification, whereas the role of surface colour is limited to the early perceptual stages for noncolour diagnostic objects. For the naming of colour and noncolour diagnostic objects, colour 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 colour information confers to the initial visual stages, our results showed a colour effect in the later stages of object identification restricted for colour diagnostic objects. At the later visual processing stages, colour information might activate a more extensive object semantic network. When we see an object, colour and shape are likely to be processed in parallel, in an interactive fashion. 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 colour 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 colour effects observed in studies that used colour diagnostic objects and studies that used noncolour diagnostic objects. Studies that used colour diagnostic objects were found to have a strong effect of colour; compared to the studies that used noncolour diagnostic objects, for which only a marginally significant effect of colour information was observed. Previous research has established

a role for colour in the early and late stages of object recognition; however, these studies either did not control for the colour diagnosticity status of the objects or only used high-colour diagnostic objects (Davidoff, 1991; Davidoff, Walsh, & Wagemans, 1997; Gegenfurtner & Rieger, 2000; Goffaux et al., 2005; Lu et al., 2010; Proverbio et al., 2004; Wurm, Legge, Isenberg, & Luebker, 1993). For example, Davidoff (1991) proposed a model of object recognition in which colour 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 colour is processed at the early visual stages, and that there are separate representations for colour and shape, but that these representations are richly interconnected. Thus, colour objects can activate colour representations that in turn activate associated shape representations (Humphreys et al., 1994; Price & Humphreys, 1989).

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

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Manuscript received October 2011
Manuscript accepted October 2012
First published online November 2012