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Neurophysiological evidence for categorical perception of color

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ABSTRACT

The aim of this investigation was to examine the time course and the relative contributions of perceptual and post-perceptual processes to categorical perception (CP) of color. A visual oddball task was used with standard and deviant stimuli from same (within-category) or different (between-category) categories, with chromatic separations for within- and between-category stimuli equated in Munsell Hue. CP was found on a behavioral version of the task, with faster RTs and greater accuracy for between- compared to within-category stimuli. On a neurophysiological version of the task, event-related potentials (ERPs) showed earlier latencies for P1 and N1 components at posterior locations to between- relative to within-category deviants, providing novel evidence for early perceptual processes on color CP. Enhanced P2 and P3 waves were also found for between- compared to within-category stimuli, indicating a role for later post-perceptual processes.

1. Introduction

Although the color spectrum is continuous, we perceive it as a number of qualitatively discreet ‘perceptual categories’ that we label in English with terms such as *red*, *green*, *yellow*, *and blue*. Categorical differences between colors also appear to affect color discrimination. For example, adults are faster and more accurate at discriminating between two colors that cross a category boundary (between-category), than two colors from within the same category, even when the difference in hue is equated for between- and within-category stimulus pairs (e.g., Bornstein & Korda, 1984). This is termed Categorical Perception (Harnad, 1987), and equivalent effects are found in other domains such as speech perception (e.g., Pisoni & Tash, 1974) and perception of facial expressions (e.g., Etcoff & Magee, 1992).

Despite the robustness and generality of the category effect shown in color CP, the nature of CP is a matter of debate. On the one hand, as the term implies, the category effect could be due to greater perceptual discriminability around category boundaries than discriminability within categories (e.g., Harnad, 1987). Such ‘warping’ of color space could be innate (e.g., Bornstein, Kessen, & Weiskopf, 1976; Franklin & Davies, 2004), or it could be learned under the influence of language, as the Whorfian hypothesis suggests (e.g., Davies & Corbett, 1997; Roberson, Davidoff, Davies, & Shapiro, 2004). On the other hand, the category effect could be due to the direct or ‘on-line’ use of language during task performance (e.g., Kay & Kempton, 1984; Roberson & Davidoff, 2000). Comparison of some form of linguistic representation, such as a label, could contribute to discrimination decisions (e.g., Bornstein & Korda, 1984; Caramazza, 1997).

The argument over perceptual versus linguistic accounts of CP is unresolved because performance on many of the tasks used to investigate color CP could be influenced by perceptual processes, or by linguistic processes, or by both. To determine whether linguistic or perceptual processes (or both) underpin color CP, manipulations that differentially affect linguistic and perceptual processes are required, such as blocking the use of language (e.g., Pilling, Wiggett, Özgen, & Davies, 2003; Roberson & Davidoff, 2000; Winawer et al., 2007), or using ‘markers’ that indicate the presence (or absence) of perceptual and linguistic processes. To this end, some neurophysiological markers of perception are found to be generally impervious to semantic and syntactic manipulations. These include early event-related potential (ERP) components, such as the P1 and N1 (see below; see also Khateb et al., 1999; Rugg & Coles, 1995), making an ERP approach a powerful means of examining perceptual contributions to color CP. The current investigation therefore takes a new approach to investigating the nature of CP, using ERPs to assess the contribution of early perceptual processes to the effect. The contribution of later post-perceptual processes can also be assessed, but any conclusions here must be limited as later ERP components may reflect a number of different processes, including linguistic or memorial (e.g., Rugg & Coles, 1995).

Because of their excellent temporal resolution, ERPs recorded during a typical CP-task have the potential to show when categorical effects occur during the processing stream, and to distinguish early perceptual effects from later post-perceptual (possibly linguistic) effects (see Rugg & Coles, 1995). The ‘oddball’ paradigm — detecting infrequent (deviant) stimuli among high-frequency (standard) stimuli — is particularly appropriate for the examination of categorical

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perception as the waveforms elicited by deviant stimuli correspond to processes involved in event categorization. Previous neurophysiological demonstrations of non-color CP in adults, for example, reveal evidence for larger amplitude and earlier onset ERP components to between-category relative to within-category stimuli, in oddball studies investigating phoneme CP (e.g., Chudaduangratn, Sittiprapaporn, & Kotchabhakdi, 2004; Dehaene-Lambertz, 1997) and CP of facial expressions (e.g., Campanella et al., 2002; Rossignol, Anselme, Vermeulen, Philippot, & Campanella, 2007).

The succession of ERP waves elicited by an oddball paradigm is P1, N1, P2, N2 and P3, where P and N indicate positive-going and negative-going components, respectively, and the number indicates a component's ordinal position within the waveform. The P1 component ($\sim$80–120 ms post-stimulus) and the early phase of the N1 component ($\sim$130–190 ms post-stimulus) correspond to early perceptual and sensory processes in the brain (e.g., Polich, 1999). These components have been localized to extrastriate regions of occipital cortex (e.g., Di Russo, Martinez, Sereno, Pitzalis, & Hillyard, 2002), and they are sensitive primarily to the physical characteristics of sensory stimuli, but have also been shown to be modifiable by manipulations of attention (e.g., Luck, Woodman, & Vogel, 2000; Sanders & Astheimer, 2008; Taylor, 2002). The P2, N2 and P3 components (210–270, 280–340, 350–600 ms, post-stimulus, respectively), with their broad scalp distributions, reflect primarily post-perceptual stimulus evaluation processes, and are exquisitely sensitive to target probability (Patel & Azzam, 2005). Low probability (deviant) stimuli have been shown to elicit enhanced P2, N2 and P3 waveforms in comparison with high probability (standard) stimuli (e.g., Luck & Hillyard, 1994; Patel & Azzam, 2005). The P3 component, in particular, has received substantial attention in the literature. Two primary subcomponents of the P3 have been identified: P3a and P3b (see Polich, 2007, for a review). The P3a has been linked to the top–down switching of attention by frontal brain systems towards rare or physically alerting stimuli (e.g., McCarthy, Luby, Gore, & Goldman-Rakic, 1997), whereas the P3b has been proposed to reflect subsequent context-updating and memory storage operations in temporal/parietal areas (e.g., Donchin & Coles, 1988; Donchin, Spencer, & Dien, 1997), and is particularly sensitive to the task relevance of a stimulus. These two components frequently overlap in time and are not always easy to distinguish. In this report, the P3 label refers to either of these components.

There has been one previous published ERP study of color CP (Fonteneau & Davidoff, 2007). In this study, the authors used an oddball task requiring the detection of infrequent cartoon characters among a stream of frequent color 'patches'. There were two kinds of color stimuli in a block, a frequent color and an infrequent (deviant) color differing only in hue (constant lightness and saturation), but no differential response to the colors was required. The critical manipulation was the nature of the difference between the two colors: they were either from the same category (two greens: G1–G2) or from adjacent categories (a green and a blue: G1–B1) but the hue difference between stimuli in a pair was the same for within- and between-category pairs.

Analysis of the ERP waveforms revealed several differences for within- and between-category conditions. First, the deviant stimulus elicited an ERP with greater amplitude relative to the frequent stimulus (oddball effect) within the 160–200 ms time range for both the between-category and the within-category pairs, and this extended to the 160–280 ms time range for the within-category pair only. The longer time range of this oddball effect for the within-category pairs was interpreted as evidence for more difficult within- than between-category discrimination.

Second, Fonteneau and Davidoff calculated difference waves where the waveform for the standard stimulus was subtracted from the waveform for the deviant stimulus, for both between- and within-category conditions. The peak latency (the time at which the ERP amplitude reached its maximum) for the between-category difference waveform occurred at 195 ms, which is 19 ms earlier than for the within-category difference waveform. This difference in peak latency for within- and between-category conditions was interpreted as a neural correlate for color CP. The effect arose over a *late* phase of the N1 time frame (i.e., post-190 ms), arguably reflecting processes that relate to post-perceptual stages of stimulus classification and target probability. Such an interpretation is consistent with previous study findings (see, e.g., Hopf, Vogel, Woodman, Heinze, & Luck, 2002; Ritter, Simson, & Vaughan, 1983; Vogel & Luck, 2000). Ritter et al. (1983), for example, argued that whereas the early phase of the N1 corresponded to discriminative perceptual processing, the late phase of the N1 extending into the N2 component reflected subsequent post-perceptual stimulus classification.

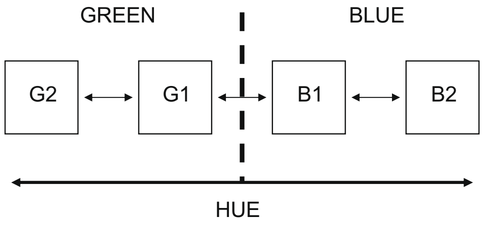

Fig. 1. Diagrammatic representation of four stimuli: two blue (B1 and B2) and two Green (G1 and G2). The dashed line represents the blue–green boundary. Stimulus separations in adjacent pairs are equated in hue difference.

The study we report here also looked for differences for within- and between-category deviants in the ERP trace, but differed in a number of ways from Fonteneau and Davidoff's study. First, as with their study, each block contained standard and deviant stimuli, but in our case there were two deviant colors, one from the same linguistic color category as the standard, and one from a different linguistic color category. For example, for the standard B1 (a blue), the deviant stimuli were B2 (a different blue) and G1 (a green; see Fig. 1). Second, we used much smaller within-pair color differences than Fonteneau and Davidoff. Our largest hue difference was about half their's ($\sim$25ΔE compared to 56ΔE).[1] Our hue separations are more typical of those normally used in color CP experiments, where 2.5–5 hue steps in Munsell color space[2] ($\sim$12–25ΔE) are com-

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[1] ΔE is the Euclidean distance between two points in the CIE ($L^*u^*v^*$, 1976) color space. L is lightness, u^* is the red–green axis and v^* the blue–yellow axis (see Hunt, 1987). The color space is appropriate for describing differences in color appearance, where equal distances in the space are intended to correspond with equal perceptual distances.

[2] *The Munsell system.* Munsell color space has three dimensions: *Hue, Value* (lightness) and *Chroma* (colorfulness, rather like saturation). In Munsell notation, the higher the Value the lighter the colors are, and the higher the Chroma, the more colorful they are. The Hue dimension is circular, as in Newton's color circle, and the Hue is designated by abbreviations of five main Hues: R (red), Y (yellow), G (green), B (blue) and P (purple), and combinations of the main hues such as BG to designate intermediate hues. Within a Hue segment, variations in Hue are indicated by numbers preceding the Hue code, such as 7.5BG, 10BG 1B, 5B etc. (see Fig. 2).

The original Munsell system was intended to be perceptually uniform — equal numerical separations within a dimension represent equal perceptual differences — but there were faults in the spacing. The spacing was adjusted based on an extensive program of psychophysical judgments (40 English speaking observers making some 3,000,000 judgments; Newhall, Nickerson, & Judd, 1943). The judgments were made using variants of the 'ratio method'; for instance, observers made magnitude judgments of the ratio of the perceived Hue difference between pairs A–B, B–C and A–C, with Chroma and Value held constant (Newhall, 1939). At the revised color spacing, at constant Chroma, equal numerical differences in Hue represent equal perceptual differences across the Hue scale. Our stimuli were taken from the Green (G) to Blue (B) segment of the Hue scale (see Fig. 2) at constant Chroma (7) and Value (5) and the Hue differences between adjacent pairs were equal within each set of four Hues at 5 and 7.5 Hue steps. Note that the perceptual distance between Hue steps increases with Chroma; Fonteneau and Davidoff's (2007) stimuli were at Chroma 10 compared to our Chroma 7, and thus the separations cannot be compared within the Munsell system; rather we have used CIE distance to make the comparison (see footnote 1).

monly used (e.g., Drivonikou et al., 2007). Note, we are not suggesting that these rather unusual features of their stimuli undermine their results, but it would be useful to check that equivalent results obtain when more standard procedures are used. Further research is also needed to clarify whether color CP can occur before the completion of perceptual processing, as this was not clearly demonstrated in Fonteneau and Davidoff's study. It is known that top–down attention, through the implementation of 'attentional sets,' can facilitate perceptual sensitivity at even the earliest stages of visual processing (e.g., Luck et al., 2000; Sanders & Astheimer, 2008; Taylor, 2002). It is possible therefore, that sensitivity to early perceptual effects of CP will be greater if attention is explicitly directed towards the color dimension for the detection of deviant color stimuli. Therefore, in contrast to Fonteneau and Davidoff's task, which required the detection of irrelevant cartoon characters, here, we asked participants to engage in the explicit detection of deviant color stimuli, and also presented stimuli for a longer duration of 400 ms (their presentation time was 200 ms). A further difference between the two studies is that whereas Fonteneau and Davidoff recorded ERPs up to 300 ms post-stimulus onset, we recorded up to 1000 ms, to establish the presence of classic 'oddball' P3 effects to infrequent color stimuli, thereby confirming the reliability of our task. Finally, in contrast to their study, we also assessed CP effects using behavioral measures.

Behavioral data were collected on a separate group of participants using reaction time (RT) and accuracy as the dependent variables to establish the suitability of our version of the oddball task for testing for color CP. In both ERP and behavioral tasks, two sets of stimuli were used to reduce the risk of habituation to the oddball stimuli. A naming task confirmed that the stimuli were named green and blue as intended. In the behavioral version of the task, it was predicted that a color CP effect would be revealed by a pattern of faster and more accurate identification of between- relative to within-category stimuli.

In the ERP task, mean amplitude and peak latency measures of the P1, N1, P2, N2 and P3 components were compared first across standard and deviant stimuli, in order to detect the presence of a typical oddball (deviant stimulus) effect. Next, these components were compared across within- and between-category deviant stimuli so as to assess the temporal characteristics of the categorical perception of color. A stimulus control ERP task was also conducted to assess whether perceptual differences between the color stimuli, such as differences in salience or detectability, would be present in the form of differential ERPs even when the stimuli were presented outside of the context of within- and between-category events. A sequence of each of the test stimuli was presented alone and ERPs recorded.

2. Methods

2.1. Stimuli and apparatus

The stimuli were from the blue–green region of color space and consisted of two sets of four colors varying only in Munsell hue; chroma (saturation) and value (lightness) were constant at 7 and 5, respectively (see Fig. 2). Within each set the separation in Munsell hue units between adjacent stimuli was equal (at 5 units for set 1 and 7.5 units for set 2). The two sets were further divided into triads of adjacent stimuli consisting of a standard plus a within-category deviant and a between-category deviant. One triad had the boundary blue as standard and the other had the boundary green (see Table 1).

Each stimulus was a square with a visual angle of 7.3°, centered in the middle of the monitor screen on a gray background ($Y = 65.49$, $x = 0.316$, $y = 0.345$). The same gray color was used for the blank screen that separated stimulus presentations. Stimuli were presented on a calibrated 21-in Sony Trinitron CRT monitor (model GDM-F520) with a Dell Pentium 4 computer. Stimulus presentation was controlled with E-Prime software (Schneider, Eschman, & Zuccolotto, 2002). Chromaticity co-ordinates of stimuli were verified with a Cambridge Research Instruments ColorCal colorimeter at regular intervals throughout the data collection period.

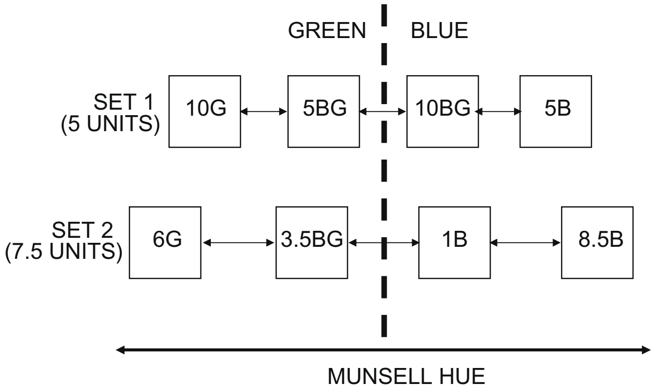

Fig. 2. Munsell codes of the stimuli for set 1 (5 Munsell hue unit separations) and set 2 (7.5 Munsell hue unit separations). The dashed line shows the intended green–blue linguistic boundary.

Table 1
Stimulus triads taken from the two sets of stimuli

Triad	Set	Stimulus type		
		S	WD	BD
1	1	5BG	10G	10BG
2	1	10BG	5B	5BG
3	2	3.5BG	6G	1B
4	2	1B	8.5B	3.5BG

Standard (S), within-category deviant (WD) and between-category deviant (BD) stimuli are indicated for each triad.

2.2. Naming task

2.2.1. Participants

Thirty-five volunteers did the naming task (18 women and 17 men; 18–35 years old; mean age: 23.8 years). Informed consent was obtained from all participants.

2.2.2. Procedure

Participants were seated in a dark laboratory, 70 cm away from the computer screen, and this arrangement was adopted for all tasks. Participants did the naming task after the behavioral or ERP tasks (see sections below). The eight stimuli were presented in a randomized order for 400 ms each and were separated by an inter-trial interval that varied randomly between 1300 and 1600 ms. Participants were instructed to press one of two buttons on a response box (left or right) to signify what color they perceived each stimulus to be (their choice being limited to either green or blue). They were asked to do this as quickly and as accurately as possible. The assignment of 'green' and 'blue' to each response button was counterbalanced across participants.

2.3. Behavioral task

2.3.1. Participants

Twenty-one participants who took part in the naming task also took part in the behavioral task (11 women and 10 men; 18–35 years old; mean age: 23.6 years). All had normal or corrected-to-normal vision and had no sign of 'red–green' color vision deficiency as assessed by the Ishihara test for color blindness (Ishihara, 1987).

2.3.2. Procedure

There were four blocks of 92 trials (one block for each triad), with the standard repeated 76 times (82%), and deviant within-category and deviant between-category stimuli occurring 8 times (9%) each. This resulted in a total of 368 trials (304 standard; 32 deviant within-category; 32 deviant between-category). The order of the four blocks was counterbalanced across participants. Each sequence of 92 trials started with the presentation of eight standard stimuli, and there were no immediate repetitions of deviant stimuli. Participants were instructed to press one of two buttons on a response box (left or right) to indicate the type of stimulus (standard or deviant), as quickly and as accurately as possible. Response button assignments were counterbalanced across participants. Stimuli were presented for 400 ms and were separated by an inter-trial interval that varied randomly between 1300 and 1600 ms. These stimulus parameters were chosen on the basis of piloting and previous oddball investigations. A practice block of 100 trials was performed before the experimental session. The practice block was split into two halves, each half using a different triad, and each triad consisting of hues that differed from those used in the experimental trials.

2.4. ERP task

2.4.1. Participants

Fourteen participants took part in the ERP task prior to completing the naming task (7 women and 7 men; 18–34 years old; mean age: 24.2 years). All had normal or corrected-to-normal vision and had no sign of red–green color vision deficiencies as assessed by the Ishihara test for color blindness (Ishihara, 1987).

2.4.2. Procedure

The ERP task had twice the number of trials as the behavioral task to ensure that there were sufficient numbers of trials for ERP analysis. There were four blocks of 184 trials (one block for each triad), and within each block the standard was repeated 152 times (82%), and deviant within-category and deviant between-category stimuli occurred 16 times (9%) each. This resulted in a total of 736 trials (608 standard; 64 deviant within-category; 64 deviant between-category). Each block was divided into two sessions of 92 trials, and there was a self-paced break in between each session. The order of the four blocks was counterbalanced across participants. Each sequence of 92 trials started with the presentation of eight standard stimuli, and there were no immediate repetitions of deviant stimuli. Participants were asked to mentally count the number of deviant (target) stimuli within each consecutive sequence of 92 trials. Counting of deviant stimuli was chosen (rather than using button-press responses) to eliminate contamination by motor-related ERP activity. A short pause was allowed at the end of each sequence for the participant to report the number of deviant stimuli to the experimenter. Additional rare stimuli were included so that the number of deviant stimuli would not be identical (i.e., $N = 16$) on each occasion. An additional rare within-category stimulus was included in one of the blocks ($N = 17$), an additional rare between-category stimulus was included in another of the blocks ($N = 17$), and two instances of rare category stimuli (one within, and one between) were included within the final block ($N = 18$). Stimuli were presented for 400 ms and were separated by an inter-trial interval that varied randomly between 1300 and 1600 ms. A practice block of 100 trials was performed before the experimental session. The practice block was split into two halves, each half using a different triad, and each triad consisting of hues that differed from those used in the experimental trials. Participants were instructed to maintain their gaze at the center of the screen, and were also asked to minimize eye blinks and to avoid any unnecessary movement.

2.4.3. ERP recording

EEG was recorded from Ag–AgCl electrodes and the average of left and right earlobe references from Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, O1, lz, O2, PO9, PO10 (according to the 10–20 system). Horizontal electrooculogram (HEOG) was recorded bipolarly from the outer canthi of both eyes. The impedance for electrodes was kept below 5 kΩ, and EEG and EOG were sampled online with a digitization rate of 1000 Hz. Following EEG recording, data were down-sampled to 200 Hz to save later computation time, and were digitally filtered with a low-pass filter at 40 Hz using Neuroscan software (version 4.3).

EEG and HEOG were epoched off-line relative to a 100 ms prestimulus baseline. Trials with lateral eye movements (HEOG exceeding ± 30 μV), as well as trials with vertical eye movements, eye blinks (Fp1/Fp2 exceeding ±60 μV), or other artifacts (a voltage exceeding ±60 μV at any electrode) measured after target onset, were excluded from analysis. The percentages of trials included after artifact rejection were: 61% of standard trials, 60% of between-category deviant trials, and 59% of within-category deviant trials.

2.5. Stimulus control ERP task

2.5.1. Participants

A separate sample of 10 volunteers took part in a control task (5 women and 5 men; 24–34 years old; mean age: 26.9 years). Data from one participant were discarded due to high levels of noise and eye blink artifacts. All had normal or corrected-to-normal vision and were screened for 'red–green' color vision deficiencies using the Ishihara test for color blindness (Ishihara, 1987).

2.5.2. Procedure

The experimental set up was the same as for the behavioral, ERP and naming tasks. The eight stimuli were presented individually in blocks consisting of 60 trials (one block per stimulus), giving a total of 480 trials. The order of the eight blocks was randomized across participants. Stimuli were presented for 400 ms and were separated by an inter-trial interval that varied randomly between 1300 and 1600 ms. Participants were just required to fixate the center of the monitor where the stimulus was presented.

3. Results

3.1. Naming task

The pattern of naming was on average 96% consistent with the intended nominal categories for each of the colored stimuli, con-

Table 2
The percentage of participants that gave the intended color name for each stimulus, for Sets 1 and 2

	Stimulus	Percentage agreement with intended name
Set 1	10G	97.1
	5BG	82.9
	10BG	100
	5B	100
Set 2	6G	100
	3.5BG	91.4
	1B	100
	8.5B	100

firming the presence of the green–blue linguistic boundary for both stimulus sets. The percentages of participants giving the intended name to the stimuli are given in Table 2.

3.2. Behavioral task

3.2.1. Accuracy

Overall accuracy for correct identification of stimuli as standard or deviant was 94% ($SD = 4$), and over the three color stimulus conditions, the mean accuracy was highest for standard stimuli (97%, $SD = 3$), lowest for deviant within-category stimuli (71%, $SD = 17$), and intermediate for deviant between-category stimuli (90%, $SD = 9$). A one-way repeated measures ANOVA revealed a significant main effect of stimulus type (standard/deviant within-category/deviant between-category), ($F(2,40) = 40.54$, $MSE = 3714.13$, $p < .001$). Planned linear (Helmert) contrasts showed significant differences in accuracy for standard vs. deviant conditions ($F(1,20) = 45.26$, $MSE = 5692.82$, $p < .001$), and for within- vs. between-category deviant stimuli ($F(1,20) = 36.57$, $MSE = 7266.09$, $p < .001$).

3.2.2. RTs

Trials with errors were discarded (less than 7%) and trials with RTs greater than 3 standard deviations (*SD*s) away from the mean (less than 2% of trials) were excluded from the RT analysis. A one-way repeated measures ANOVA with a factor of stimulus type (standard/deviant within-category/deviant between-category) was conducted on the remaining participants' correct RTs. A main effect of stimulus type ($F(2,40) = 54.32$, $MSE = 89604.98$, $p < .001$) was due to responses being fastest to standard stimuli ($M = 293$ ms, $SD = 132$), slowest to deviant within-category stimuli (417 ms, $SD = 114$), and intermediate to deviant between-category stimuli (390 ms, $SD = 105$). Planned linear (Helmert) contrasts revealed a significant difference between standard and deviant RTs, ($F(1,20) = 66.43$, $MSE = 256482.64$, $p < .001$). The difference between deviant within- and deviant between-category conditions was also significant, ($F(1,20) = 11.33$, $MSE = 16443.8$, $p < .01$).

3.3. ERP task

3.3.1. Data analysis

Separate averages were computed for all stimulus types (standard, deviant within-category, deviant between-category). Fig. 3 shows ERPs, across a representative sample of electrode sites where original EEG recording took place, elicited in response to standard (solid lines) and deviant (dashed lines for within-category; gray lines for between-category) stimuli. Analyses of variance were conducted on ERP mean amplitudes and peak latencies obtained for specific sets of electrodes within predefined measurement windows. Analyses focused on anterior (F3/4, F7/8, FC5/6), posterior (CP5/6, P3/4, P7/8), and midline (Fz, Cz, Pz) electrodes. These analyses were conducted for ERP mean amplitudes and peak amplitudes in response to stimuli elicited within successive post-stimulus time intervals (P1-window: 80–120 ms; 'early phase' N1-window: 130–190 ms; P2-window: 210–270 ms; N2-window: 280–340 ms; P3-window: 350–600 ms). These time windows were determined on the basis of prior research (see Rugg & Coles, 1995, for a review) and inspection of individual subject waveforms. The analysis was done in two stages. First, oddball effects were tested by comparing amplitudes and peak latencies of components for standard and deviant stimuli (averaged across within- and between-category deviants). This analysis of oddball effects was performed to establish whether a typical pattern of ERP waveforms would be generated to deviant colors. Second, category effects were tested by comparing deviant within-category and deviant between-category stimuli. The earlier occurrence of P1 and N1 components to between-category stimuli would suggest rapid perceptual processing of category effects, whereas enhanced P2, N2 or P3 components would suggest the involvement of later cognitive or linguistic processes. For all the analyses, repeated measures ANOVAs were conducted for the electrode sites indicated above, with hemisphere (left/right) as a factor for the analyses of anterior and posterior electrode sites only, and electrode position (i.e., caudality; with three levels) for each of the analyses of anterior (F3/4, F7/8, FC5/6), posterior (CP5/6, P3/4, P7/8), and midline (Fz, Cz, Pz) electrode sites. Note that hemisphere was included as a factor because the potential emergence of a left hemispheric bias for category effects could be indicative of linguistic influences (see, e.g., Drivonikou et al., 2007; Gilbert, Regier, Kay, & Ivry, 2006). For all analyses, Greenhouse-Geisser adjustments to the degrees of freedom were performed to correct for sphericity violations.

3.3.2. Oddball effects (standard vs. deviant stimuli)

3.3.2.1. Mean amplitude. No reliable ERP oddball effects were present within the P1 (80–120 ms post-stimulus) or N2 (280–340 ms post-stimulus) time ranges at any electrode site, or within the 'early phase' N1 time range (130–190 ms post-stimulus) for anterior or midline electrodes. In contrast, a larger N1 component was elicited at posterior sites to deviant as compared with standard stimuli ($F(1,13) = 7.28$, $MSE = 57.13$, $p < .05$, -0.5 μV deviant, 0.6 μV standard). A greater amplitude to deviant compared to standard stimuli was also observed within the P2 (210–270 ms post-stimulus) time range at anterior ($F(1,13) = 4.95$, $MSE = 64.72$, $p < .05$, 1.1 μV deviant, -0.2 μV standard) and midline ($F(1,13) = 10.81$, $MSE = 94.14$, $p < .01$, 3.5 μV deviant, 1.3 μV standard) sites. As expected, a prominent positivity with a broad distribution across electrodes was evident for deviant relative to standard stimuli within the P3 time range (350–600 ms post-stimulus). This observation was substantiated by statistical analyses. An oddball effect was obtained within the P3 measurement window at anterior ($F(1,13) = 5.99$, $MSE = 119.26$, $p < .05$, 1.2 μV deviant, -0.5 μV standard), midline ($F(1,13) = 18.84$, $MSE = 384.33$, $p < .01$, 4.6 μV deviant, 0.3 μV standard), and posterior ($F(1,13) = 31.95$, $MSE = 465.65$, $p < .001$, 3.9 μV deviant, 0.6 μV standard) electrodes. The main effects of stimulus type (standard vs. deviant) were accompanied by interactions between stimulus type and recording hemisphere at anterior electrode sites (all $F(1,13) > 4.80$; all $p < .05$), as mean amplitude differences were greater for left- as compared with right-hemisphere locations.

3.3.2.2. Peak latencies. Analyses of peak latencies revealed the earlier onset of P1 ($F(1,13) = 13.48$, $MSE = 1050.0$, $p < .01$, 97.7 ms deviant, 102.7 ms standard), N1 ($F(1,13) = 5.36$, $MSE = 1400.15$, $p < .05$, 152.9 ms deviant, 158.7 ms standard), and N2 ($F(1,13) = 4.80$, $MSE = 7400.15$, $p < .05$, 298.6 ms deviant, 311.9 ms standard) components for deviant as compared against standard conditions at posterior electrodes only. There was no evidence of earlier peak latencies in deviant conditions for P2 components, and analyses of peak latencies within the P3 window were not conducted due to the absence of any identifiable peaks for standard condition components within this time range.

Inspection of grand-averaged (see Fig. 3) and individual participant waveforms also suggested the presence of a post-P300 slow wave (SW). This is a slow shifting, sustained negativity believed to reflect the retention of information in working memory (Gray, Ambady, Lowenthal, & Deldin, 2004; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992). It is likely that the increased information load required by the counting and maintenance of deviant items in working memory for later report was responsible for this effect.

3.3.3. Category effects (deviant within-category vs. deviant between-category stimuli)

3.3.3.1. Mean amplitude. No significant main effects of category for mean amplitude were obtained within P1, 'early phase' N1, and N2

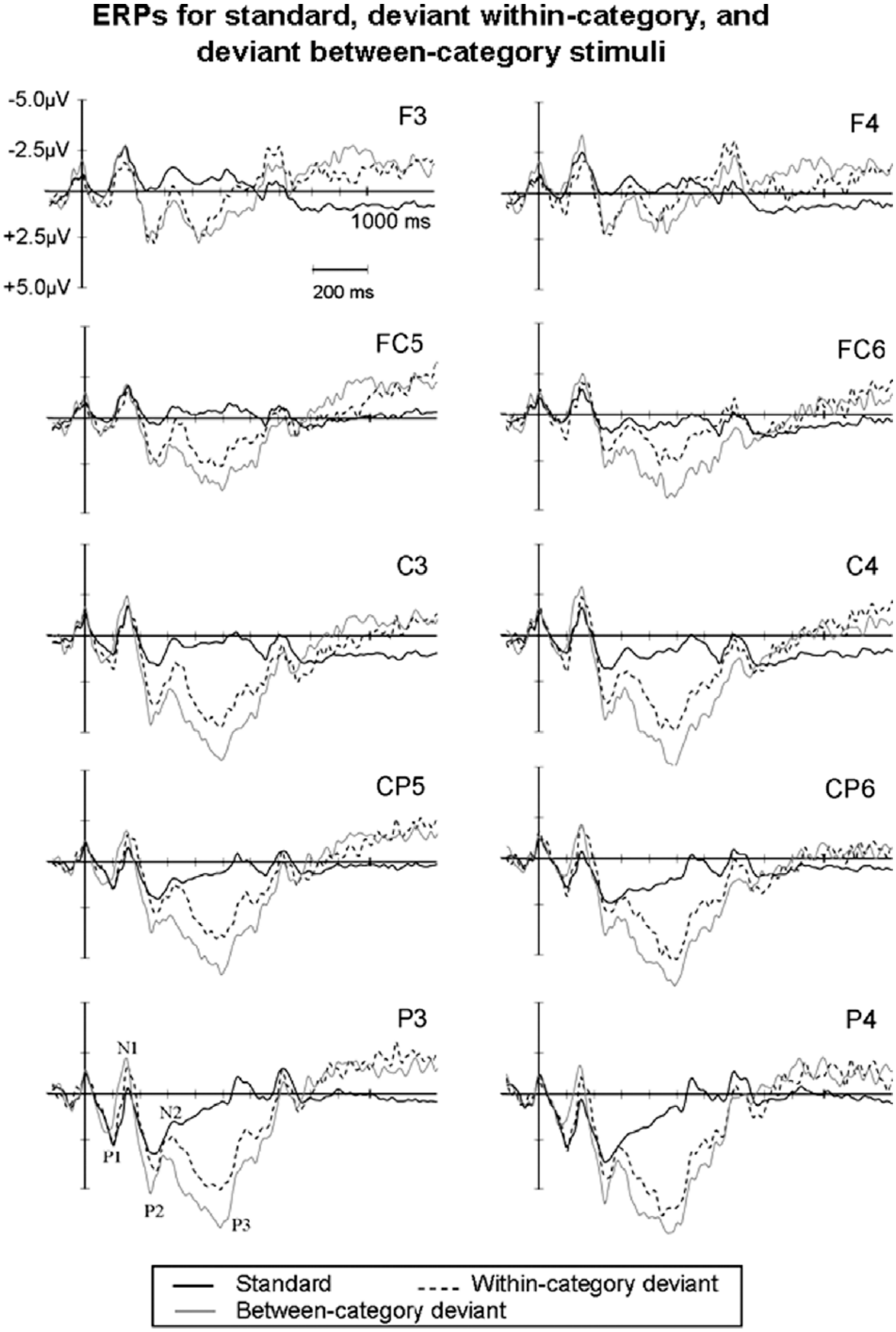

Fig. 3. Grand-averaged ERP waveforms elicited in the 1000 ms interval following stimulus onset in response to standard (black solid lines), within-category deviant (black dashed lines), and between-category (gray lines) color stimuli.

measurement windows. A greater positivity for deviant between-category stimuli was observed within the P2 time window at posterior sites ($F(1,13) = 5.01$, $MSE = 34.94$, $p < .05$, 3.1 µV between-category, 2.1 µV within-category). Enhanced positive amplitudes for deviant between- relative to deviant within-category stimuli were also found within P3 time windows at anterior ($F(1,13) = 10.62$, $MSE = 68.75$, $p < .01$, 1.9 µV between-category, 0.6 µV within-category), midline ($F(1,13) = 7.05$, $MSE = 54.64$, $p < .05$, 5.4 µV between-category, 3.8 µV within-category), and posterior ($F(1,13) = 8.03$, $MSE = 75.43$, $p < .05$, 4.7 µV between category, 3.2 µV within-category) electrodes. Finally, there were no significant interactions between category and recording hemisphere (largest $F = 3.89$, smallest $p = .07$).

3.3.3.2. Peak latencies. Analyses of peak latencies revealed the emergence of earlier peaks for between- relative to within-category stimuli across the following time windows and electrode sites: P1 peak at midline electrodes ($F(1,13) = 5.0$, $MSE = 629.76$, $p < .05$, 90.7 ms between-category, 96.2 ms within-category), N1 peaks at midline ($F(1,13) = 5.07$, $MSE = 1001.19$, $p < .05$, 146.6 ms between-category, 153.5 ms within-category) and posterior ($F(1,13) = 11.31$, $MSE = 3762.05$, $p < .01$, 148.5 ms between-category, 157.9 ms within-category) electrodes, and, finally, N2 peaks at anterior ($F(1,13) = 4.56$, $MSE = 2251.34$, $p = .052$, 306.8 ms between-category, 314.1 ms within-category) and posterior ($F(1,13) = 6.63$, $MSE = 3128.72$, $p < .05$, 296.3 ms between-category, 304.9 ms within-category) electrode sites. There was no evidence of earlier peak latencies in between-category conditions for P2 components, and analyses of peak latencies within the P3-window were not conducted in order to maintain comparability with the analyses for oddball effects (standard vs. deviant stimuli).

3.3.4. Counting task

The mean performance for identifying the occurrence of oddball events was 97% (*SD* = 6), which confirms that participants were attending to the stimuli.

3.4. Stimulus control ERP task

3.4.1. Data analysis

Separate averages were computed for the four colors comprising each of the stimulus sets (see Fig. 2). Analyses of variance were conducted on peak latencies for the P1 and N1 (i.e., perceptual) measurement windows. Peak latencies were obtained for specific sets of electrodes within these predefined measurement windows (see ERP task above for details). Effects of stimulus were tested by comparing peak latencies of components across the four colors that made up each separate stimulus set. These analyses were performed to ascertain that there were no ERP differences between the colors that might explain any category-specific ERP effects at perceptual stages of processing.

3.4.2. Stimulus effects

Importantly, there were no significant main effects of stimulus for peak latencies across either Set 1 or Set 2 (all $Fs < 1.73$, all $ps > .20$) for either of the measurement windows.

4. Discussion

4.1. Summary of findings

The aim of the present study was to investigate the time course of categorical perception of color by recording ERPs. This approach allows an assessment of the relative contributions of early perceptual and later post-perceptual strategies to color CP. Color CP was investigated across the green–blue boundary, using two sets of stimuli. A naming task confirmed that the stimuli straddled the green–blue linguistic boundary. A visual oddball task was used to assess CP, in which deviant between- or within-category stimuli had to be detected against the context of a series of standard stimuli. On the behavioral version of the task, participants responded as to whether stimuli were standard (frequent) or deviant (infrequent) and the behavioral measures of accuracy and reaction time were analyzed. As expected, responses were fastest and most accurate to standard compared with deviant stimuli. There was also a category effect on the task, with faster responses and higher accuracy for between-category relative to within-category stimuli, consistent with well-established behavioral findings of categorical perception (e.g., Bornstein & Korda, 1984). This confirmed that the visual oddball task and the two stimulus sets were suitable for the investigation of the time course of CP. On an ERP version of the oddball task, a separate group of participants counted the number of deviant stimuli and event-related potentials were recorded. Analysis of the ERP signals revealed patterns typical of oddball detection, as well as patterns indicating differential responses to within- and between-category stimuli (category effects). Finally, a stimulus control ERP task clarified the independence of these category effects from any simple perceptual differences between the color stimuli. These ERP effects are discussed in detail in the following sections.

4.2. ERP oddball effects: comparisons of standard and deviant stimuli

As in previous studies, our ERP data show typical oddball detection effects (see Patel & Azzam, 2005; Polich, 2007, for reviews). These consist of late (P2 and P3) effects indicating the detection of infrequent events by post-perceptual processes, and early (N1) effects indicating a rapid detection of infrequent events by perceptual processes that may originate in visual brain areas (e.g., Di Russo et al., 2002). An enhanced N1 to infrequent visual stimuli has been reported before (e.g., Czigler, Balazs, & Pato, 2004; Kenemans, Grent't, Jong, & Verbaten, 2003; Potts, Patel, & Azzam, 2004), but is a less robust finding than P2 and P3 oddball effects. Laterality effects at frontal sites for these components were also present, with greater oddball effects at left- as compared with right-hemisphere locations. This may reflect an effect of language due to the participants' occupation with the counting task.

4.3. ERP Category effects: comparison of within- and between-category deviants

A pattern of effects emerged that was consistent with categorical perception, with earlier and more pronounced ERP components to deviant between-category stimuli across a number of electrode sites and measurement windows. ERP patterns reflecting categorical effects were evident early in the waveform (P1 and 'early phase' N1), indicating the involvement of perceptual processes in categorical perception of color, and to a lesser extent, at later stages (P2, N2 and P3), indicating a role for post-perceptual processes. Moreover, the control task showed there were no differences in sensory ERPs when stimuli were presented independently of a category-specific stimulus context, indicating that the effects must reflect processes involved in the comparison of stimuli (detection of differences).

4.3.1. Early effects

Shorter ERP latencies to between-category relative to within-category stimuli were evident for P1 and 'early phase' N1 components. These components are described in visual ERP studies as reflecting early visual processing, and are found to be sensitive to variations in the physical characteristics of an eliciting stimulus and also to the focus of spatial attention (see reviews by Hillyard, Vogel, & Luck, 1998; Mangun, 1995). Striate and extrastriate origins are proposed for posterior P1 and N1 components (Di Russo et al., 2002; Gomez, Clark, Luck, Fan, & Hillyard, 1994; Heinze et al., 1994). An early perceptual contribution to color CP is therefore suggested by these results, providing an account that is compatible with findings in the auditory domain, which reveal that perception of phonemic categories takes place at a very early stage in signal processing (e.g., Dehaene-Lambertz, 1997; Näätänen, Lethokoski, Lennes, & Cheour, 1997). The early visual CP effect in the current study could reflect a modulation of the P1 and N1 components as a result of clearer perceptual discrimination for between-category as compared to within-category stimuli. The P1 and N1 components have been shown previously to differentiate between, for example, words or faces and other objects (e.g., Schendan, Ganis, & Kulas, 1998), and between animals and vehicles (e.g., VanRullen & Thorpe, 2001). However, these early ERP effects may have reflected differences in 'low-level' visual properties (e.g., luminance, contrast energy, or spatial scale) of the stimulus categories involved. By contrast, our findings provide arguably one of the first clear demonstrations of visual categorization on early perceptual ERP components, which cannot be explained simply in terms of 'low-level' perceptual differences. This is because the color separations for standards relative to within-category deviants, and for standards relative to between-category deviants, were of equal magnitude, and did not evoke ERP differences when presented in isolation during the control task. The current results are in line with previous suggestions that category effects on early ERPs reflect the extent to which the observer may have 'expertise' or long-term experience with the categories involved (e.g., Schendan et al., 1998), or the extent to which some category distinctions (e.g., facial emotion; see Eimer & Holmes, 2007) are hard-wired or convey inherent biological significance (see, e.g., Mollon, 1989, for a discussion of the evolution of color vision and the biological advantages of color categorization for perceptual identification). Either way, the effect of color CP is clearly arising at distinctly early stages of processing.

Effects of color categorization on ERPs were also shown recently by Fonteneau and Davidoff (2007) using a passive visual oddball paradigm, but the CP modulations in their study arose later than those found in the current study. Color categorization effects in our study arose between 90 and 100 ms (P1) and again between 145 and 160 ms ('early phase' N1). By contrast, in the Fonteneau and Davidoff study, differences arose between 195 and 215 ms ('late phase' N1), and were therefore not clearly interpretable as *perceptual* markers of color CP (cf. Hopf et al., 2002; Ritter, Simson, Vaughan, & Macht, 1982; Ritter et al., 1983; Vogel & Luck, 2000). The nature of the task being performed may account for the temporal differences between the two studies. Whereas explicit attention to the color dimension was required for the detection of deviant color stimuli in the current study, it was not required in the Fonteneau and Davidoff study, but rather participants were asked to detect incidental cartoon characters. This difference could be responsible for the CP latency differences across the two studies, as attention to 'color' may have increased the sensitivity of the task to potential color CP effects in our study. An examination of the modulation of color categorization effects by varying task demands should be addressed in future research.

In summary, the current findings of P1 and 'early phase' N1 ERP effects to deviant stimuli provide novel neurophysiological evidence for the role of early perceptual processes in CP of color.

4.3.2. Late effects

Although ERP latency effects were evident predominantly for early components, differences in mean amplitudes were also found to emerge at later epochs. More specifically, between-category stimuli elicited larger P2 and P3 amplitudes than within-category stimuli. These results for later ERP components are consistent with findings from a recent electrophysiological study investigating categorical perception of facial expression (e.g., Campanella et al., 2002), which also found enhanced P3 components to between-category stimuli. As was stated earlier in the introduction, these components (P2, P3) are usually linked with processes of stimulus evaluation (Patel & Azzam, 2005), and incorporate essentially any post-perceptual process that is not related to the preparation of an overt response (e.g., McCarthy & Donchin, 1981). Consequently, it would be difficult to identify the specific psychological processes involved in color CP at these later stages of analysis. However, it remains a clear possibility that processes such as verbal labeling may contribute to 'late' color CP effects in this study (see, e.g., Friedman, Cycowicz, & Dziobek, 2003, for evidence of language effects on late ERP components such as the P3), although it should also be noted that a left hemispheric bias, which might be expected according to a linguistic account (e.g., Drivonikou et al., 2007; Gilbert et al., 2006), was not present for these category-specific ERP differences.

5. Conclusion

Although the effect of color CP is well established in behavioral studies, the nature of color CP has been under considerable debate. This debate has focused on whether color CP is influenced primarily by perceptual processes or by linguistic processes. A number of behavioral studies have examined this issue by looking directly at the contribution of language to the effect (e.g., Franklin & Davies, 2004; Gilbert et al., 2006; Kay & Kempton, 1984; Roberson & Davidoff, 2000). Here, an alternative approach was taken to understanding the nature of color CP, by examining neural 'perceptual' markers of the effect. In order to establish the contribution of early perceptual processes to CP, ERPs were recorded on a visual oddball task. Unlike the results of a previous ERP study (Fonteneau & Davidoff 2007), category effects in the ERPs were found in early perceptual components (P1 and an early phase of N1), with category effects apparent as early as 90 ms. In addition, there were also category effects detectable at later stages (P2, P3) indicating a later, post-perceptual contribution to color CP. Linguistic accounts of color CP are post-perceptual explanations, and therefore our data, which implicate perceptual as well as post-perceptual mechanisms, imply that a linguistic theory of color CP is at best incomplete. Crucially, these findings provide novel neurophysiological evidence for the influence of categories on color processing at early perceptual stages.

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