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Color Categories Affect Pre-Attentive Color Perception

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Abstract

Categorical perception (CP) of color is the faster and/or more accurate discrimination of colors from different categories than equivalently spaced colors from the same category. Here, we investigate whether color CP at early stages of chromatic processing is independent of top-down modulation from attention. A visual oddball task was employed where frequent and infrequent colored stimuli were either same- or different-category, with chromatic differences equated across conditions. Stimuli were presented peripheral to a central distractor-task to elicit an event-related potential (ERP) known as the visual mismatch negativity (vMMN). The vMMN is an index of automatic and pre-attentive visual change detection arising from generating loci in visual cortices. The results revealed a greater vMMN for different-category than same-category change detection when stimuli appeared in the lower visual field, and an absence of attention-related ERP components. The findings provide the first clear evidence for an automatic and pre-attentive categorical code for color.

Introduction

The spectrum of color is continuous, yet we can carve this continuum up into a number of discrete categories using the color terms in our language (e.g., *red*, *green*, *blue*). Color categories also appear to be present in our color perception and cognition. For example, judging whether two colors are different is faster and / or more accurate if the two colors are from different color categories (between-category) than from the same category (within-category: e.g., Bornstein & Korda, 1984). In addition, visual search for a colored target is faster and / or more accurate when the target and distractors are between- than within-category (e.g., Pilling, Wiggett, Özgen, & Davies, 2003). These category effects are present despite the between- and within-category chromatic differences being equated in various color metrics.

The nature of this ‘categorical perception’ (CP) of color has been extensively investigated (see Regier & Kay, 2009 for a review). Most recently, Event-Related Potential (ERP) and functional Magnetic Resonance Imaging (fMRI) techniques have been employed to establish the time course and neural correlates of color CP (Clifford, Franklin, Davies, & Holmes 2009; Fonteneau & Davidoff, 2007; Holmes, Franklin, Clifford, & Davies, 2009; Liu et al., 2009; Siok et al., 2009). These studies have provided evidence for the contribution of both perceptual processes and post-perceptual processes such as language. For example, correlates of faster between- than within-category color search have been found in language related brain regions (LH posterior temporoparietal region, middle temporal gyrus and inferior prefrontal cortex), as well as regions of visual cortex (V2/V3: Siok et al., 2009). Correlates of color category effects in regions of visual cortex appear to indicate that a categorical code for color is registered at early stages of chromatic processing.

Further evidence for early category effects comes from ERP studies that have used visual oddball tasks. For example, within the context of the frequent repetition of one color

(the standard), ERP components elicited in response to a less frequently presented color (the deviant) peak earlier and/or have greater amplitude when the standard and deviant are between- than within-category. This category effect is found even for early perceptual components such as P1 and N1 (Fonteneau & Davidoff, 2007; Holmes et al., 2009). However, the extent to which early color category effects are due to top-down modulation from later processes such as language and attention is currently unclear. In the studies of Siok (2009) et al. and Holmes et al. (2009), as participants were required to attend to color and make an explicit judgment on the basis of color, top-down modulation effects cannot be ruled out. In Fonteneau and Davidoff's (2007) study, color was not task relevant and an explicit judgment on the basis of color was not required — participants were required to detect cartoon characters interspersed amongst the presentation of colors. It was suggested that the category effect in their study arose 'without attention focused on color' (p.1326) on the basis that no participant reported that the task was concerned with color, and that ERP waveforms did not appear to have the typical distribution for 'attention selection effects' (see Näätänen, 1988). On the other hand, it would be surprising if the simple task of detecting the presence or absence of a cartoon character presented at a different time to the colors would prevent participants from attending to the large and chromatically distinct stimuli used in the study.

In the current study, we further investigated the nature of color category effects at early stages of perceptual processing by recording ERPs to standard and deviant colors that were within- or between-category, whilst participants completed an engaging color-irrelevant task (press a key whenever a centrally presented fixation marker changed shape). There is likely to be less attention to color than in Fonteneau and Davidoff's (2007) study, as the color-irrelevant distractor task of the current study should be more engaging, the distractor stimuli were presented at the same time as the colors, and the chromatic difference was much smaller. Previous research that has used this distractor task in combination with a visual

oddball task, found that deviant stimuli elicited a deviance-related component known as the visual mismatch negativity (vMMN: Czigler, Balázs, & Pató, 2004). The vMMN is suggested to be an index of automatic, non-attentional encoding of the violation of regularities in the visual world, and a marker of low-level, pre-attentive perceptual processing (see Czigler, 2007). The current study aims to establish whether color category effects are apparent in this ERP component. If the vMMN has a greater amplitude for between- than within-category color deviance, this would suggest that the categorical code for color is present at early stages of chromatic processing, even in the absence of top-down modulation from attention.

Due to the overlapping time course of the vMMN (~100-250 ms) with an attention-related negativity known as the N2b that is also sensitive to mismatch detection, (see Folstein & Van Petten, 2007, for a review), it is necessary to establish that a deviance related negativity (DRN) in this time range is indeed a vMMN. Fortunately, the vMMN has distinctive characteristics that set it apart from the N2b. First, unlike the N2b, the vMMN is not accompanied by a P3a. The P3a is an anterior component that is linked to the explicit top-down switching of attention by frontal brain systems towards rare or physically alerting stimuli and forms part of what is known as the N2b/P3a complex (see Polich, 2007, for a review). Second, the vMMN has a more posterior distribution than the N2b, the latter of which is maximal at fronto-central locations. Third, the vMMN tends to start earlier than the N2b (~100 ms versus ~200 ms post-stimulus onset, respectively). Fourth, the vMMN has a right hemisphere dominance (Cammann, 1990). Finally, the vMMN is far more pronounced for stimuli (at least for color stimuli) appearing in the lower visual field – potentially reflecting the retinotopic organization of visual cortex (Czigler et al., 2004). In the current study, standard and deviant colored stimuli were presented in both upper and lower visual fields and the characteristics of the elicited waveforms were assessed in order to establish

whether the DRN recorded within the vMMN time window was a vMMN or an attention related N2b.

Method

Participants

Eighteen students (9 female, 9 male) with a mean age of 26.7 years (SD = 5.3) participated in the experiment. All had normal or corrected-to-normal vision and were screened for red-green color vision deficiency using the Ishihara test for color blindness (Ishihara, 1987). Data from two additional participants were not included due to an insufficient number of artifact-free trials.

Apparatus and experimental set-up

A 21-inch Sony Trinitron CRT monitor (model GDM-F520) with a Dell Pentium 4 computer was used and stimulus presentation was controlled with Visual Basic software (with ExactTics high resolution timer). Participants were seated 70 cm away from and at eye level to the centre of the monitor in a darkened laboratory.

Stimuli and Design

The stimuli were square patches of three computer-generated colors from the blue-green region of color space, as used by Gilbert et al. (2006). The standard (7.5BG) and the within-category deviant were both blue (2.5B), and the between-category deviant (2.5BG) was green. These stimuli varied only in Munsell Hue, and Munsell Chroma and Value were constant at 6 and 8, respectively¹. The between- and within-category deviants were each 5 Munsell Hue units from the standard. The chromaticity co-ordinates of stimuli were verified with a Cambridge Research Instruments ColorCal colorimeter (see Table 1).

Stimuli were presented on a grey background ($Y = 30.05$, $x = 0.313$, $y = 0.319$). Stimuli were displayed either above or below a central fixation point, in either the upper (UVF) or

lower visual field (LwVF). The stimulus display and its dimensions are given in Figure 1. On each trial, the outer square was either the standard (7.5BG; 80% of trials), the within-category deviant (2.5B; 10% of trials) or the between-category deviant (2.5BG; 10% of trials). In addition, on all trials a central rectangular patch was always 7.5BG. The rectangular patch overlapped with a marker that was located at the central fixation point of the screen (see Figure 1). This central marker was either a cross (91% of trials) or a circle (9%). The stimulus display (outer square and rectangular patch) subtended a vertical visual angle of 7.3 degrees from the central fixation point. The central marker was either a 2 cm x 2 cm black cross (distractor) or a 2 cm diameter black circle (target).

There were twelve blocks of 110 trials, which resulted in a total of 1320 trials. The outer square was the standard for 1056 trials and the within- and between-category deviant for 132 trials each. Each square and rectangular patch arrangement appeared in the UVF for half of the trials and in the LwVF for the other half of the trials. The ratio of standard, within-category deviant and between-category deviant stimuli was maintained for each visual field. Central distractor stimuli (crosses) appeared for 100 of the 110 trials in each block and central target circle stimuli (circles) appeared for 10 of the 110 trials in each block, which resulted in a total of 1200 distractor trials and 120 target trials. Each visual field assignment and the ratio of each stimulus type occurred across these two conditions with equal probability.

Each trial began with a 0.5 cm diameter central fixation dot appearing on a grey background. The duration of this 'inter-trial interval' (ITI) varied randomly between 800 and 1200 ms. The colored stimuli were presented for 200 ms. All trial types were randomized across blocks, with the proviso that each block began with the presentation of 8 standard stimuli and that there were no immediate repetitions of deviant or target stimuli. See Figure 1 for an example of the sequence of trial events.

Procedure

The participant's task was to press the space bar with both index fingers each time a central target stimulus appeared, and they were asked to do this as quickly and as accurately as possible. Participants were informed that a series of colored squares and rectangles would appear on the screen but that they should ignore these and maintain central focus. They were also asked to minimize eye blinks and avoid any unnecessary movement, and were allowed a self-paced break in between each block.

EEG recording

EEG was recorded 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, Iz, O2, PO9, PO10 and the average of left and right earlobe references according to the 10-20 system (Jasper, 1958), using Ag-AgCl electrodes. Horizontal electro-oculogram (HEOG) was recorded bipolarly from the outer canthi of both eyes. The impedance for electrodes was kept below 5 k Ω , and EEG and EOG were sampled on-line with a digitization rate of 1000 Hz, and were digitally filtered with a band-pass filter of 0.1 to 100 Hz using Neuroscan software (version 4.3). Following EEG recording, a low-pass filter of 40 Hz was applied, and the data were down-sampled to 200 Hz to save later computation time. EEG and HEOG were epoched off-line with a window extending to 700 ms after stimulus onset, relative to a 100 ms pre-stimulus baseline. Trials with lateral eye movements (HEOG exceeding ± 30 μ V), as well as trials with vertical eye movements, eye blinks (Fp1/Fp2 exceeding ± 60 μ V), or other artifacts (a voltage exceeding ± 60 μ V at any electrode) measured after target onset, were excluded from analyses. Target trials and false alarms were also excluded from analyses. A minimum of 30 artifact-free trials for each stimulus condition was required for inclusion of any one participant's data in the final sample. Trial numbers were matched across stimulus conditions to the condition containing the least number of accepted trials, for each participant. Included trials were

selected randomly from all available trials. The resulting mean number of included trials per stimulus condition was 38.8 ($SD = 7.2$).

ERP data analysis

Separate averages were computed for the mean amplitude of each stimulus type (standard, within- and between-category deviant) and visual field (UVF and LwVF) in order to test for the presence of a deviance-related negativity (DRN: greater negativity to the deviant than the standard) within the vMMN (100-250 ms) time window. This temporal interval was selected *a priori* on the basis of previous research (Czigler, 2007; Pazo-Alvarez et al., 2003). Inspection of the grand averages suggested that a DRN in the LwVF may have extended beyond the pre-selected time window (see Cammann, 1990, for similar findings). Therefore, an additional interval of 250-350 ms was used to examine the possible extended time course of a DRN. Electrode sites Pz, Iz, O1 and O2 were selected for analyses of the DRN as this component is typically greatest over posterior areas (Czigler, 2007; Pazo-Alvarez et al., 2003) and was observed from the grand averaged waveforms to be most pronounced at these sites. Separate averages were also computed for time windows covering the N2b/P3a complex (250-350 ms; 350-600 ms; see Folstein & van Petten, 2007; Näätänen & Gaillard, 1983). Recordings were taken from electrode sites Cz and Fz as previous research has shown the N2b/P3a complex to have a centro-frontal scalp distribution. Finally, averages were computed within the 350-600 ms time range for the posterior P3b component at electrode sites Pz, Iz, O1 and O2, as a P3b could be indicative of explicit attention to the peripheral color patches (see Patel & Azzam, 2005; Polich, 2007).

The DRN was analyzed using a three-way within-subjects analysis of variance (ANOVA). The ANOVA factors were Stimulus (standard, within- and between-category deviant), Visual Field (UVF, LwVF), and Electrode (Pz, Iz, O1, O2). It is important to note that the presence of a DRN is reflected by a greater negativity to the within- or between-

category deviant than to the standard. Although the standard is included as a level within the factor of Stimulus, this is done for the purposes of comparison, as by definition DRN is not elicited by the standard. A 'category effect' is shown by a greater negativity to the between- than to the within-category deviant. The P3b was analyzed using exactly the same factors and levels, and the N2b and P3a components were also analyzed in the same way, except for the difference in the levels of the factor Electrode (Cz, Fz). Results are reported for all main and interaction effects involving the factor of Stimulus. Significant main effects of Stimulus were followed up using Bonferroni-corrected paired samples *t* tests for the following comparisons: within-category deviant vs. standard (within-category DRN), between-category deviant vs. standard (between-category DRN), and within-category deviant vs. between-category deviant (category effect). Greenhouse-Geisser adjustments to the degrees of freedom were performed where appropriate to correct for sphericity violations (Jennings & Wood, 1976).

Results

Behavioral results

Mean accuracy for the central target task was 99.5% (SD = 0.7), which confirmed that participants attended to the central target stimuli.

ERP results

DRN (100-250 ms; posterior sites). Figure 3 shows that for stimuli in the LwVF, a larger negative mean amplitude is apparent for the between-category deviant relative to the standard (i.e., between-category DRN) and within-category deviant (i.e. category effect), whereas the mean amplitude for the within-category deviant appears no different from that of the standard. For the UVF there appears to be no larger negative mean amplitude for the between- and within-category deviant relative to the standard, or to each other (see Figure 2).

ANOVA revealed a marginally significant main effect of Stimulus, $F(2,34) = 3.27, p = .05, \eta_p^2 = .16$, and, consistent with initial impressions from the figures, there was a significant interaction between Stimulus and Visual Field, $F(2,34) = 11.57, p < .001, \eta_p^2 = .41$. Figure 4 shows the mean amplitudes for this interaction, collapsing across Electrode. The interaction was followed up with one-way ANOVAs for the UVF and LwVF conditions separately. A significant main effect of Stimulus was found for the LwVF, $F(2,34) = 12.18, p < .001, \eta_p^2 = .42$, but not the UVF, $F(2,34) = 1.23, ns$. The LwVF difference was investigated further using paired samples t tests (with a Bonferroni-corrected significance level of $p < .017$), which revealed a between-category DRN, $t(17) = 4.11, p < .01, d = 0.86$, but not a within-category DRN, $t(17) = 1.15, ns$. A significant category effect was also found, $t(17) = 3.49, p < .01, d = 0.79$. Notably, the Stimulus by Visual Field interaction was subsumed under a significant interaction between Stimulus, Visual Field, and Electrode Site, $F(2,34) = 3.76, p < .05, \eta_p^2 = .18$, as the between-category DRN in the LwVF was less pronounced at site O1 (left hemisphere) than at other electrode sites (O2, Pz, Iz: right hemisphere and midline), consistent with previous demonstrations of a right hemispheric dominance for the vMMN (e.g., Cammann, 1990). The Stimulus by Electrode interaction from the overall ANOVA failed to reach significance, $F(6,102) = 1.89, ns$.

DRN (100-250 ms in 50 ms epochs; posterior sites). Further analyses were performed to investigate the pattern of results across narrower epochs of 50 ms within the DRN time range. Crucially, the pattern of a larger negative mean amplitude for the between-category deviant relative to the standard (i.e., between-category DRN) and within-category deviant (i.e. category effect) in the LwVF only was apparent in all three epochs. However, these differences were strongest in the 150-200 ms time range. ANOVA revealed that within the 100-150 ms epoch, there was a significant interaction between Stimulus and Visual Field, $F(2,34) = 4.87, p < .05, \eta_p^2 = .22$. This crucial interaction was followed up with separate one-

way ANOVAs for the UVF and LwVF conditions, which showed a significant main effect of Stimulus for the LwVF, $F(2,34) = 3.66, p < .05, \eta_p^2 = .18$, but not the UVF, $F(2,34) = 1.04, ns$. The LwVF difference was investigated further using paired samples t tests (with a Bonferroni-corrected significance level of $p < .017$). These revealed neither a within-category DRN, $t(17) = 1.83, ns$, nor a between-category DRN, although the between-category DRN was approaching significance, $t(17) = 2.35, p = .031, d = 0.35$. There was no category effect, $t(17) = 1.25, ns$.

Within the 150-200 ms time range there was an interaction between Stimulus and Visual Field, $F(2,34) = 13.03, p < .001, \eta_p^2 = .43$. No significant main effect of Stimulus was found for the UVF, $F(2,34) = 2.91, ns$, but there was a significant main effect of Stimulus for the LwVF, $F(2,34) = 14.87, p < .001, \eta_p^2 = .47$. Paired samples t tests (with a Bonferroni-corrected significance level of $p < .017$) revealed a between-category DRN, $t(17) = 4.16, p < .005, d = 1.65$, but not a within-category DRN, $t(17) = 2.32, ns$. A category effect was also found, $t(17) = 4.23, p < .005, d = 0.63$.

An interaction between Stimulus and Visual Field was also found within the 200-250 ms time range, $F(2,34) = 4.56, p < .05, \eta_p^2 = .21$. A significant main effect of Stimulus was revealed for the LwVF, $F(2,34) = 5.32, p < .01, \eta_p^2 = .24$, but not the UVF, $F(2,34) = 0.17, ns$. Paired samples t tests (with a Bonferroni-corrected significance level of $p < .017$) showed no within-category DRN, $t(17) = 0.50, ns$, and no between-category DRN within the LwVF, although the between-category DRN was very close to significance, $t(17) = 2.59, p = .019, d = 0.55$. A category effect was present, $t(17) = 2.67, p = .016, d = 0.66$.

Extended DRN (250-350 ms; posterior sites). Similar to the pattern of the DRN within the 100-250 ms time window, in the LwVF, the between-category deviant appears to elicit a larger negative mean amplitude than both the standard (between-category DRN) and the within-category deviant (category effect), whereas the within-category deviant does not differ

from the standard (see Figure 3). For the UVF there appears to be no larger negative mean amplitude for the between- or within-category deviant relative to the standard, or to each other (see Figure 2). However, these initial impressions were not supported as ANOVA revealed that the interaction between Stimulus and Visual Field just failed to reach significance, $F(2,34) = 3.04, p = .06$. The mean amplitudes for this interaction, collapsing across Electrode can be seen in Figure 4. The interaction between Stimulus and Electrode also failed to reach significance, $F(6,102) = 2.06, p = .07$. Finally, the main effect of Stimulus was non-significant, $F(2,34) = 1.01, ns$, and so was the interaction between Stimulus, Visual Field and Electrode, $F(6,102) = 1.84, ns$.

N2b (250-350 ms; anterior sites). It appears from Figures 2 and 3 that at electrode site Cz, but not Fz, the between-category negativity may be larger than the standard and within-category negativity in the LwVF, but not the UVF. These initial impressions were partially confirmed by the presence of significant interactions between Stimulus and Electrode, $F(2,34) = 7.28, p < .01, \eta_p^2 = .30$, and Stimulus, Visual Field, and Electrode, $F(2,34) = 4.06, p < .05, \eta_p^2 = .19$. The three-way interaction was followed up with two-way ANOVAs for Cz and Fz electrodes separately, but no significant interaction between Stimulus and Visual Field was found for either electrode (largest $F = 1.90$, smallest $p = .17$). Finally, the overall ANOVA revealed no main effect of Stimulus, $F(2,34) = 1.61, ns$, and no interaction between Stimulus and Visual Field, $F < 1$.

P3a (350-600 ms; anterior sites). Inspection of Figures 2 and 3 indicates that there is no positivity in either visual field in response to the between-category or the within-category deviant relative to the standard, or to each other. The absence of any P3a or category effects was confirmed by statistical analyses, which revealed no main effect or interactions involving Stimulus (largest $F = 1.97$, smallest $p = .16$).

P3b (350-600 ms; posterior sites). No larger positivity in either visual field for the between-category or the within-category deviant relative to the standard, or to each other, is apparent from Figures 2 and 3. The absence of any P3b or category effects was confirmed by statistical analyses, which revealed no main effect or interactions involving Stimulus (largest $F = 1.60$, smallest $p = .22$).

Difference potentials. An additional analysis was conducted to investigate the difference waveforms (see Figure 5). Here the DRN was calculated by subtracting ERPs to standard stimuli from ERPs to between-category stimuli (the between-category DRN), and ERPs to standard stimuli from ERPs to within-category stimuli (the within-category DRN). The difference waveforms were analysed in the same way as the original mean amplitudes for all time ranges, except for the difference in the factor Stimulus, which had two levels rather than three (within-category DRN, between-category DRN). This analysis revealed a similar pattern of results to the original analysis and is summarized below.

Within the DRN time range (100-250 ms, posterior sites) a significant interaction between Stimulus and Visual Field was found, $F(1,17) = 6.47$, $p < .05$, $\eta_p^2 = .28$. A significant main effect of Stimulus was revealed for the LwVF, $F(1,17) = 12.16$, $p < .01$, $\eta_p^2 = .42$, (between-category DRN > within-category DRN), but not the UVF, $F(1,17) = 0.63$, *ns*. An interaction between Stimulus, Visual Field, and Electrode, $F(3,51) = 3.44$, $p < .05$, $\eta_p^2 = .17$, revealed that the category effects in the LwVF were less pronounced at site O1 (left hemisphere) than at other electrode sites. Additionally, the difference potential analysis confirmed the presence of an extended DRN (250-350 ms; posterior sites), unlike in the original analysis. A significant interaction between Stimulus and Visual Field was revealed, $F(1,17) = 6.71$, $p < .05$, $\eta_p^2 = .28$. No significant main effect of Stimulus was found in the UVF, $F(1,17) = 0.85$, *ns*, but there was a significant main effect of stimulus in the LwVF, $F(1,17) = 5.14$, $p = .05$, $\eta_p^2 = .23$, (between-category DRN > within-category DRN). Within

the N2b time range (250-350 ms; anterior sites) there was a significant interaction between Stimulus, Visual Field, and Electrode, $F(1,17) = 7.91, p < .05, \eta_p^2 = .32$. However, no significant interaction between Stimulus and Visual Field was found for either Fz or Cz (largest $F = 3.19$, smallest $p = .09$). Finally, as was shown by the original analysis, no main effects or interactions involving Stimulus were revealed within the 350-600 ms time range for either the P3a (anterior sites; largest $F = 3.21$, smallest $p = .09$), or the P3b (posterior sites; largest $F = 1.78$, smallest $p = .16$).

Discussion

This study examined the neural correlates of color CP using a task that was designed to measure automatic and pre-attentive visual change detection. The results indicated that task-irrelevant, deviant colored stimuli elicited a DRN within the vMMN time range (100-250 ms post stimulus onset), and there was a trend for the DRN to extend in an attenuated form to 350 ms post stimulus onset. The DRN was prominent at posterior sites, yet was also found to extend to central regions but with reduced amplitude. Notably, the DRN was only significant for between-category deviants in the lower visual field, and was significantly stronger for between- than within-category deviants.

It could be argued that the late emergence of the DRN at central locations is indicative of attentional processing of deviant colors, and that the recorded negativity is in fact an attention-related N2b (or *novelty N2*) rather than a vMMN. However, there are a number of reasons why this is unlikely to be the case. First, the N2b, which has a fronto-central distribution in both the visual and auditory modality, is accompanied by a frontal positive component (P3a; see Folstein & Van Petten, 2008). The negativity recorded in the present study, however, possessed a predominantly posterior distribution, did not extend as far as frontal locations, and there was no evidence of an accompanying P3a. Second, the DRN

emerged earlier (~100 ms) than would a typical N2b (onset of ~200 ms). The extended time range of the DRN (to 350 ms) is also consistent with some previous vMMN findings (e.g., Cammann, 1990; Maekawa et al., 2005; Tales, Newton, Troscianko, & Butler, 1999). Third, like the vMMN, the DRN was present only for deviants displayed in the lower visual field (see also Czigler et al., 2004) and, consistent with one previous report (Cammann, 1990), was found to be dominant in the right hemisphere. All of these characteristics of the DRN indicate it to be a vMMN rather than an attention-related N2b. Similarly, its early onset and sensitivity to ‘non-target’ stimulus characteristics indicate that it is unlikely to be an attention-related N2c (or posterior N2) — a conclusion that is further reinforced by the observation that the negativity arose in the absence of an accompanying P3b (see, e.g., Pazo-Alvarez et al., 2003). The presentation of stimuli in central rather than lateral locations, together with the absence of contralaterality effects in the waveforms, also rules out an explanation in terms of a selection negativity (SN) or N2pc (see Folstein & Van Petten, 2008). We therefore infer that a vMMN is elicited for between- but not within-category deviants and only when deviants are presented to the lower visual field.

Another important point to consider is that because the DRN overlapped with the N1 response, the color category modulations of the ERPs may reflect simple perceptual differences between the stimuli as opposed to processes involved in the detection of visual irregularities. However, we consider this to be unlikely because the DRN extended beyond the N1 component and exhibited key characteristics of a vMMN, as described above. Furthermore, in a previous study we found no differences in early perceptual components such as the P1 and N1 between color stimuli falling within the same blue-green region of color space (Holmes et al., 2009). The specificity of the DRN to the lower visual field would also appear to preclude an explanation in terms of refractoriness (i.e., the stimulation of non-overlapping neural populations; see Czigler, 2007).

Colour category effects in ERPs have also been demonstrated by Fonteneau and Davidoff (2007) using a visual oddball task involving an unattended colour change. However, a DRN was not elicited in their study, but rather a change-related positivity (CRP), which occurred over posterior sites. As mentioned previously, the task used in their investigation involved the detection of infrequent cartoon characters, which was intended to direct participants' attention away from the coloured stimuli. Indeed, Fonteneau and Davidoff (2007) report that accuracy on this task was at ceiling, suggesting that attention was directed towards the cartoon characters. However, as discussed earlier, it is possible that participants were also attending to the coloured stimuli, which were singly presented as well as being large and chromatically distinct. This may explain why a DRN was not elicited, although the role of attention to task-irrelevant stimuli in their study is difficult to infer as the analysis window (0 to 300 ms post-stimulus) is not long enough to assess reliably the presence of other typically distributed attention-related components such as the N2b or P3a.

The current findings provide further evidence for color CP at early stages of chromatic processing (Fonteneau & Davidoff, 2007; Holmes et al., 2009; Siok et al., 2009). Source localization was not employed in the current study, yet it is likely that these early color category effects arise from regions of visual cortex. For example, it has been argued that the vMMN has generating loci in retinotopically organized parts of the visual system due to the presence of the vMMN in lower but not upper visual fields (Czigler et al., 2004). Czigler et al. (2004) suggest that the vMMN is most likely to originate from prestriate visual areas due to the longer latency of the vMMN relative to ERP components known to originate in primary visual cortex. Although previous research has also provided evidence for color category effects at early stages of perceptual processing, it has been unclear whether these effects are due to top-down modulation from post-perceptual processes. The current investigation provides compelling evidence that early color category effects can exist

independent of top-down modulation from attention. The findings indicate that, at least for the size of the chromatic difference tested here, only different-category chromatic irregularities are automatically and implicitly detected.

Further research is now needed to clarify the contribution of language to color category effects at early stages of chromatic processing. Siok et al. (2009) tentatively suggested that early category effects at visual cortex are due to top-down modulation from language related regions of the brain. One possibility is that top-down modulation occurs in the form of an explicit naming strategy, whereby attention is directed to color and color terms are employed to complete the task (e.g., Roberson & Davidoff, 2000). However, it is highly unlikely that an explicit naming strategy was employed in the current investigation, as color was task irrelevant and there were no attention-related ERP components elicited by the colored stimuli. Nevertheless, there are two alternative ways in which language could be responsible for a color category effect at early stages of chromatic processing. First, verbal codes for color may be activated unconsciously and automatically, even in the absence of direct attention to the colors. There is evidence that the lexical codes for color are activated even for rapid presentations of colors (Tan et al., 2008), yet it is unclear whether this would be the case if attention was focused on a color-irrelevant task. Second, language may warp perception of colors over time so that different category colors come to *look* more different than same category colors, even in the absence of attention to color and verbal color code activation.

A recent cross-linguistic ERP study may provide evidence that language can affect even unconscious, automatic and pre-attentive detection of chromatic irregularities (Thierry, Athanasopoulos, Wiggett, Dering & Kuipers, 2009). Thierry et al. (2009) found a stronger DRN for blue than green change detection for Greek speakers whose language has two basic blue terms (*ble* and *ghalazio*), but not for English speakers who have only one basic blue

term. However, further investigation of this effect is needed to verify that the DRN does actually reflect a vMMN. For example, the presence of a P3 to the deviant stimuli for the English sample suggests that the DRN for that sample was actually an attention-related N2b rather than a vMMN. A replication of Thierry et al. using the task of the current study (manipulating visual field) would clarify whether cross-linguistic differences are found for the vMMN. For now, the current investigation, which finds a greater vMMN for between- than within-category chromatic change detection, provides some of the first clear evidence that there is an automatic, pre-attentive categorical code for color.

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Acknowledgements

This research was supported by a departmental PhD bursary to Alexandra Clifford from the Department of Psychology, University of Surrey. We thank Sarah Ma for assistance with data collection.

Footnotes

1. Munsell is a standardized color metric that is based on an extensive program of psychophysical judgments (Newhall, Nickerson & Judd, 1943) and is a common color metric for equating colors in studies of CP (e.g., Bornstein & Korda, 1984; Gilbert et al., 2006). There are three dimensions: Hue, Value (lightness) and Chroma (colorfulness, rather like saturation). Stimuli are specified using a notation that consists of three co-ordinates that each relate to one of the three dimensions.