Brain and Cognition 71 (2009) 165–172

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Electrophysiological markers of categorical perception of color in 7-month old infants

Alexandra Clifford [a], Anna Franklin [a,*], Ian R.L. Davies [a], Amanda Holmes [b]

[a] *Department of Psychology, University of Surrey, Guildford, Surrey, GU2 5XH, England, UK*
[b] *School of Human and Life Sciences, Roehampton University, UK*

ARTICLE INFO

Article history:
Accepted 6 May 2009
Available online 5 June 2009

Keywords:
Color
Infant
Categorical perception
ERP

ABSTRACT

The origin of color categories has been debated by psychologists, linguists and cognitive scientists for many decades. Here, we present the first electrophysiological evidence for categorical responding to color before color terms are acquired. Event-related potentials were recorded on a visual oddball task in 7-month old infants. Infants were shown frequent presentations of one color (standard) interspersed with infrequent presentations of a color that was either from the same category (within-category deviant) or from a different category (between-category deviant) to the standard. Differences in the event-related potentials elicited by the stimuli were found that were related to the categorical relationship of the standard and the deviant stimuli. The data are discussed in relation to the processes that underlie categorical responding in infancy, as well as the debate about the origin of color categories in language and cognition.

© 2009 Elsevier Inc. All rights reserved.

1. Introduction

The origin and nature of color categories in language and cognition has been the concern of researchers from a range of disciplines such as psychology, anthropology, cognitive science, linguistics and philosophy, for many decades (see Bornstein, 2006, 2008). One major issue has been whether the way in which the spectrum of color is carved up into categories is arbitrary, or whether there are universal constraints on how these categories form (e.g., Berlin & Kay, 1969; Kay, 2005). Variation in how languages categorize color may suggest that this process is arbitrary. For example, there is ample evidence that the number of basic color terms and the location of color category boundaries varies across languages, and that color lexicons also evolve over time (e.g., MacLaury, Paramei, & Dedrick, 2008). However, systematic investigation of over one-hundred of the world's unwritten languages suggests there are universal constraints that underpin the color naming systems of these languages, with statistical tendencies for color categories to form at certain points in the color space (Kay & Regier, 2003; Regier, Kay, & Cook, 2005; Regier, Kay, & Khetarpal, 2007).

In support of the argument that there may be perceptual constraints on how language categorizes the spectrum of color, there is converging behavioral evidence for categorical responding to color in pre-linguistic infants (Bornstein, Kessen, & Weiskopf, 1976; Catherwood, Crassini, & Freiberg, 1987, 1990; Franklin & Davies, 2004; Franklin, Pilling, & Davies, 2005; Franklin et al., 2008). Four-month old infants, when habituated to a colored stimulus, dis-habituated to a novel color from a different (English) linguistic color category to the habituated stimulus, yet did not dis-habituate if the novel and habituated stimuli came from the same linguistic category (Bornstein et al., 1976).[1] This effect was found for same and different-category stimulus pairs equated in wavelength-differences, for red, green, yellow and blue categories. The findings have since been replicated and extended using an alternative metric (Munsell)[2] to equate same- and different-category stimulus pairs, and a novelty preference task (Franklin & Davies, 2004). These infant studies demonstrate a form of categorical responding called Categorical Perception (CP). Color CP is the faster or more accurate discrimination of two colors belonging to different categories (between-category) than two colors from the same category (within-category), even when within- and between-category chromatic

---

[*] Corresponding author.
E-mail address: a.franklin@surrey.ac.uk (A. Franklin).

[1] Habituation is the decline of looking after repeated presentation of a stimulus; dis-habituation is the reinstatement of looking in response to a novel stimulus.

[2] Munsell is a standardized color metric that is used in adult color category studies (e.g., Bornstein & Korda, 1984). The metric was based on extensive psychophysical judgments (Newhall, Nickerson, & Judd, 1943). Research suggests that the metric will be standardized for 7-month old infants as for adults. For example, by 12 weeks stimuli equated in luminance for adults will also be isoluminant for the average infant (e.g., Pereverzeva, Chien, Palmer, & Teller, 2002), and although chromatic thresholds are elevated in infancy, even by 4-months chromatic sensitivity varies similarly across different axes of color vision compared to older and adult observers (Knoblauch, Vital-Durand, & Barbur, 2001). The CIE (1976, $L*u*v*$) color metric, also used in color category studies, is not always in complete agreement with Munsell. However, category effects for infants have also been found when stimuli are equated using the CIE (1976, $L*u*v*$) color metric (e.g., Franklin et al., 2005), and infants respond categorically regardless of any difference in CIE for within- and between-category pairs (see Table 1 in Franklin & Davies, 2004).

0278-2626/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.bandc.2009.05.002

separation sizes are equated (Harnad, 1987).[3] Further evidence for color CP in infants comes from a target detection task, where 4–6-month old infants were faster at detecting a colored target on a different-category than same-category background, even though hue separations were the same across conditions (Franklin et al., 2005, 2008).

Infants' categorical responding to color is not surprising as categorization is a pervasive aspect of infant cognition (e.g., Mareschal & Quinn, 2001). However, that infants respond categorically to colors (such as blue and green) is surprising in the context that many of the world's languages do not have words for these categories. The major challenge is to establish how infants form these color categories, what perceptual and cognitive processes underlie this categorical responding, and to establish how these pre-linguistic perceptual categories may (or may not) provide constraints on linguistic color categorization later on in development.

The current investigation used an ERP technique to further investigate color CP in infancy. An ERP is the voltage change, measured from electrodes on the scalp, that occurs during a defined period of time (epoch) within which a stimulus is shown or an event occurs. Using this technique we aimed to identify the electrophysiological markers of categorical responding to color in infants. There are several reasons for taking this approach. First, if color category effects in infant ERPs are found, this would provide compelling further evidence in support of the argument that color category effects exist in the absence of language. Second, as different ERP components indicate different processes (e.g., attentional allocation, novelty detection and memory updating), the technique provides information on the mechanisms that underlie the effect, as well as providing information on the time course of the effect. Third, testing for color category effects in infant ERPs extends previous research on the neural markers of CP and categorization in infancy. The ERP approach has previously been used to investigate category effects in infancy, although there have been few studies: one for CP of phonemes (Dehaene-Lambertz & Baillett, 1998) and two for category learning (Grossman, Gliga, Johnson, & Mareschal, in press; Quinn, Westerlund, & Nelson, 2006). The current study allowed an assessment of whether the neural markers for category effects generalize across different perceptual domains (e.g., color/phonemes) and different types of categorical responding (e.g., categorical perception/perceptual categorization). Whereas categorical perception requires that same- and different-category differences are equated, perceptual categorization such as that in Quinn et al.'s study does not. However, despite these differences, there may well be similarities in the neural markers and underlying mechanisms of these two types of categorical responding.

In the current investigation, infant ERPs were recorded during a visual oddball task. The task involves frequent presentation of one stimulus (the standard), while another stimulus or other stimuli are presented less frequently (the 'oddball' or deviant; e.g., de Haan & Nelson, 1997). An oddball effect is found when there are differences between the deviant and frequent stimulus in the amplitude or latency of ERP components. The design of the current study follows that of an adult ERP study of color CP (Holmes, Franklin, Clifford, & Davies, 2009), where ERPs were recorded to deviant stimuli that were either from the same category (within-category) or from a different category (between-category) to the standard, with within- and between-category hue differences equated. In the adult study, ERP components peaked earlier and were of greater amplitude for between-category deviants compared to within-category deviants, even for very early perceptual components (P1 and N1; Holmes et al., 2009).

In infants, ERP components that are typically elicited on a visual oddball task are the Nc, the negative slow wave (NSW) and the positive slow wave (PSW; e.g., de Haan & Nelson, 1997). The Nc is a typically central negativity that peaks around 400 ms, and is commonly interpreted as a marker of attentional allocation (e.g., Richards, 2003), with pre-frontal and anterior cingulate origins (Reynolds & Richards, 2005). The positive and negative slow waves are thought to reflect more diffuse activation of neural areas, with the NSW seen as reflecting the detection of novel events against a background of familiar events, and the PSW reflecting the extent of stimulus encoding and updating in working memory (e.g., Nelson & Monk, 2001). Category effects were found in these visual ERP components for category learning of cats and dogs in 6-month old infants (Quinn et al., 2006). The current study tests whether category effects in these ERP components generalize to categorical responding for another domain and type of categorical responding.

In addition to the visual oddball task, a control task was included where ERPs were recorded to alternations of deviant stimuli in the visual oddball task. This ensured that any differences in the ERP components for the within- and between-category deviants could be attributed to the categorical status of the deviant in relation to the standard, rather than other stimulus characteristics, such as a greater salience of one hue over the other. The standard stimulus was never shown, thereby removing the categorical context of the stimuli. To aid the interpretation of any effects found in the ERP components, a behavioral post-test followed the visual oddball and control task, where looking time was recorded to the two stimuli that were deviant in the visual oddball task and that were alternately presented during the control task.

2. Method

2.1. Participants

Fifty-nine 7-month old infants took part, with 20 infants not included in the final sample due to general inattentiveness ($n = 5$) or a high number of movement artifacts in the ERP data ($n = 15$). Infants were allocated to either visual oddball or control tasks. The visual oddball task had a final sample of 20 infants (9 female and 11 male) with a mean age of 236 days (SD = 17) and the control task had a final sample of 19 infants (10 female and 9 male) with a mean age of 242 days (SD = 16). All birth weights were above 2700 grams, and no infants had a known family history of color vision deficiency. Ethical approval was granted by the University of Surrey Ethics Committee.

2.2. Stimuli

Stimuli were shown on a black background as schematic colored faces, which consisted of a colored circle with black circles for the eyes and a black ellipse for the mouth (see Fig. 2 for grayscale example; Catherwood et al., 1990). Stimuli were taken from the green–blue region, with adjacent stimuli separated by 10 Munsell hue units, with Munsell value (lightness) and chroma (saturation) kept constant (see Fig. 1). Stimuli were measured with a CRS ColorCal colorimeter (see Table 1 for CIE (1931) Y, x, y coordinates).

2.3. ERP procedure

Infants sat in a baby car seat in a darkened lab, 70 cm away from, and at eye-level to the center of a 21-in. Sony Trinitron CRT monitor (model GDM-F520). Infant looking was observed via a TV monitor. Each trial consisted of a stimulus shown for 500 ms (visual angle 9.7°) on a black background, with a minimum inter-trial interval

---

[3] Original definitions of CP required no discrimination of within-category stimuli (Lieberman, Harris, Hoffman, & Griffith, 1957), yet in the domain of color this stricter definition of CP has been revised (e.g., Bornstein & Korda, 1984).

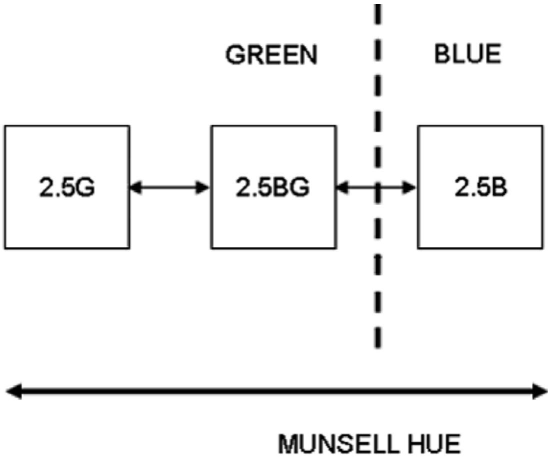

Fig. 1. Representation of the three stimuli: 2.5BG (standard); 2.5G (within-category deviant); 2.5B (between-category deviant), with adjacent stimuli separated by 10 Munsell hue units. Stimuli are constant in Munsell value and chroma. The dashed line represents the blue–green linguistic category boundary.

Table 1
Munsell codes and *Y*, *x*, *y* (CIE, 1931) chromaticity coordinates of the stimuli. The white point of the monitor was $Y = 76.25$ cd/m^2, $x = 0.313$, $y = 0.331$.

Munsell code	*Y*	*x*	*y*
2.5G 6/8	22.91	0.279	0.424
2.5BG 6/8	22.91	0.233	0.352
2.5B 6/8	22.91	0.208	0.279

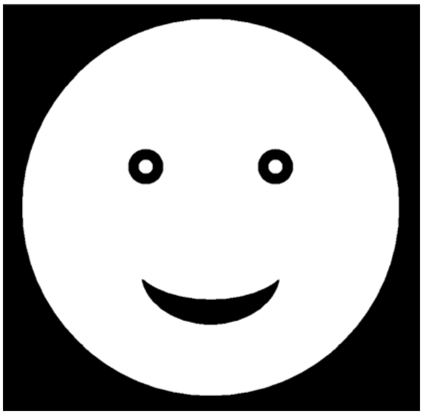

Fig. 2. Example of the schematic face used to display colored stimuli. The area that appears white was colored.

of 1300 ms during which the background remained black. Stimuli were only shown when infants were fixated centrally. If the infant looked away during testing, a black and white looming, contracting and beeping ‘attention-getter’ was presented centrally, and that trial and the subsequent trial were excluded from the analysis. The ERP session was terminated if the infant stopped looking at the display for a sustained period, or when all experimental trials were completed (maximum 120 trials).

For the visual oddball task, a green (2.5BG) was presented on 60% of trials (the standard) and a different green (2.5G) and a blue (2.5B) were each presented on 20% of trials (within- and between-category deviants, respectively). There were no immediate repetitions of deviant stimuli. For each infant, a minimum of 10 artifact free trials for each stimulus were required for inclusion in the final sample. To ensure equivalent signal to noise ratio across stimuli, an equal number of trials were included for each stimulus for a given infant. Included stimuli were randomly selected from all the available trials from each stimulus type. The mean number of included trials per stimulus was 12.6 (SD = 2.91).

For the control task, the two stimuli that were the within- and between-category deviants in the visual oddball task (2.5G and 2.5B) were presented alternately. A minimum of 10 artifact free trials for each stimulus was required for inclusion in the final sample, with an equal number of trials randomly selected for each stimulus. The mean number of trials that were included per stimulus was 33.4 (SD = 6.01). An additional analysis that selected trials from only the first 40% of trials (equivalent exposure for each stimulus relative to the visual oddball task) was conducted where the mean number of trials that were included per stimulus (12.6, SD = 0.84) matched that of the visual oddball task.

2.4. ERP recording

EEG was recorded from individual Ag–AgCl electrodes at Fz, C3, Cz, C4, Pz, and Oz, with linked-mastoid references according to the 10–20 system (Jasper, 1958). EOG was recorded bipolarly from the outer canthi of both eyes (HEOG) and from above and below the right eye (VEOG). EEG and EOG were sampled online with a digitization rate of 1000 Hz and impedances were kept below 10 kΩ but were generally less than 5 kΩ. 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. EEG and EOG were epoched off-line using Neuroscan software (version 4.3) and divided into trials consisting of 100 ms before stimulus onset (baseline) until 1700 ms after this point. Trials with lateral eye movements (HEOG exceeding ±150 μV), as well as trials with vertical eye movements, eye blinks (VEOG exceeding ±250 μV), or other artifacts (a voltage exceeding ±150 μV at any electrode) measured after target onset were excluded from analysis. Cut offs were determined by a combination of visual inspection and convention within the literature (e.g., DeBoer, Scott & Nelson, 2004; Quinn et al., 2006).

2.5. Behavioral post-test

Immediately following the visual oddball or control tasks, there were two 5-s trials of paired presentations of the two stimuli that were the deviants in the visual oddball task and that were presented alternately in the control task (2.5G and 2.5B), to the left and right of central fixation with position counterbalanced across trials. Stimuli had a visual angle of 8.36°, with the inner edge of the stimulus 4.99° from the central fixation point. Infant looking was coded blind and online by one observer, and one third of videotaped looking data was coded by two observers with good inter-rater reliability ($r = 0.93$, SD = 0.06).

3. Results

3.1. Visual oddball task

Time windows for the Nc (250–650 ms) and the NSW/PSW (1150–1700 ms) were determined on the basis of prior research and inspection of each individual’s waveforms. Fig. 3 shows the waveforms for each type of stimulus, with the Nc and NSW/PSW time frames illustrated for C3 and C4. The waveforms are given for all electrodes except Oz which was excluded from the analysis due to high levels of noise.[4] The peak amplitude of the Nc and the

---

[4] The infant ERP components implicated in infant category learning in Quinn et al.’s (2006) study (Nc, NSW, and PSW) are not restricted to Oz and are all elicited at the electrode sites that were analyzed in the current investigation (e.g., de Haan & Nelson, 1997). However, analysis of Oz (which often has a different waveform morphology) would have enabled an assessment of whether category effects are found in other components (such as P1).

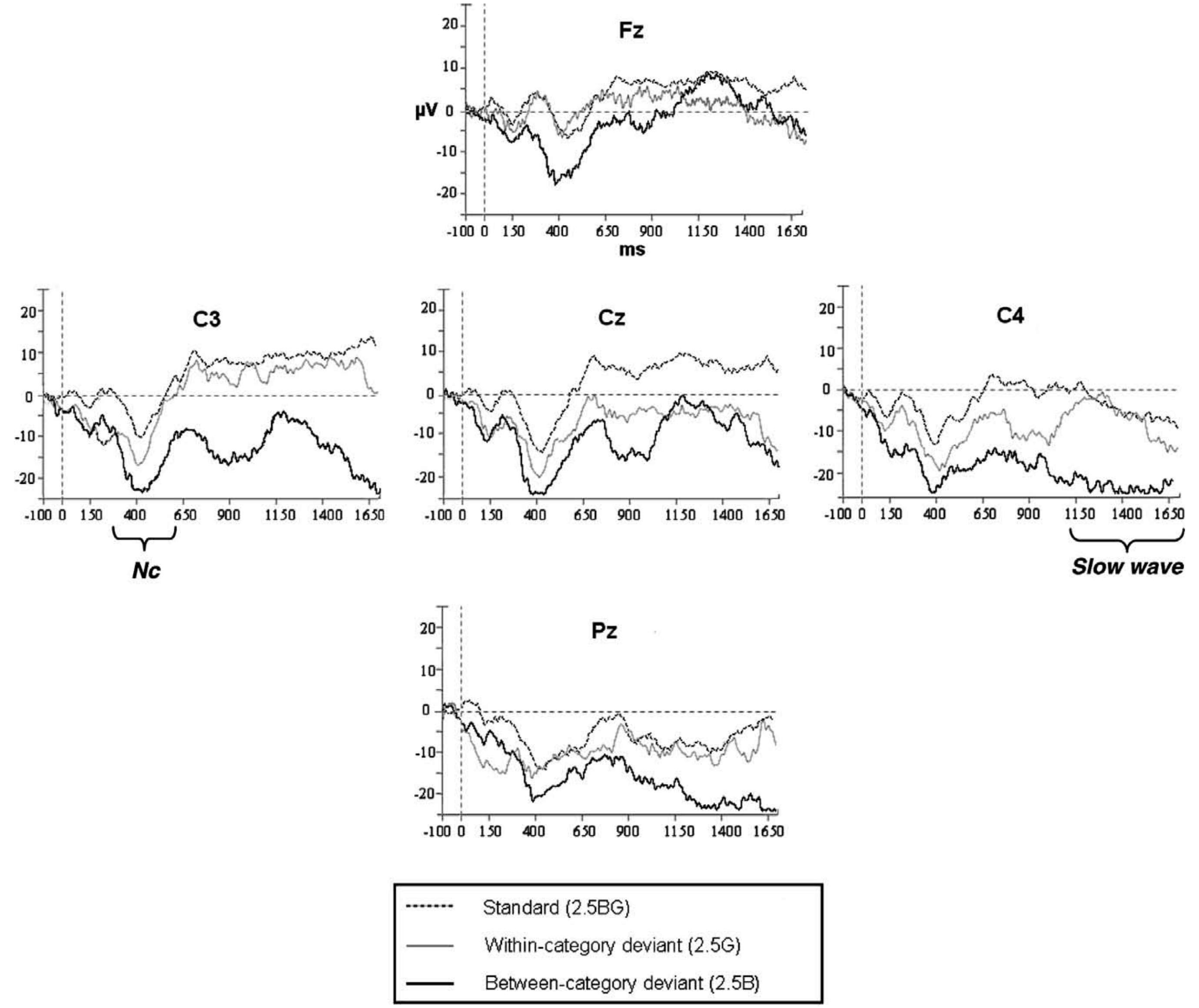

Fig. 3. Grand-averaged ERP waveforms elicited during the1700 ms following stimulus onset (0 ms) in response to standard (dashed lines), within-category deviant (gray lines), and between-category deviant (black lines) stimuli. The horizontal dashed line represents baseline (0µv). The Nc is indicated for electrode C3, and the slow wave (NSW or PSW) is indicated for electrode C4.

mean amplitude of the NSW/PSW were analyzed to test for differences across stimulus types using two-way ANOVA, with Stimulus (standard, within- and between-category deviant) and Electrode (Fz, C3, Cz, C4, and Pz) as factors. When there were significant differences across stimuli, the analysis then tested for differences in amplitude for the standard and the deviant (an oddball effect), for within- and between-category deviants separately. The amplitude for within- and between-category deviants was also compared. Equivalent exploratory analyses were also conducted on the two remaining time ranges: 100–250 ms (where there is a minor positive component at some sites), and 650–1150 ms (where there is a negative component, possibly an early NSW: Ackles & Cook, 2007).

3.1.1. Nc component

Differences in Nc amplitude across stimuli were consistent with categorical responding. As can be seen in Fig. 3, it appears that at all electrodes, the between-category deviant has a larger negative amplitude than both the standard (an oddball effect) and the within-category deviant, while the latter two have similar amplitudes. Two-way ANOVA confirmed that there were significant differences in the Nc peak amplitude across stimuli (means, (SD): standard = −11.57 µv, (11.20); within-category deviant = −15.81 µv, (8.90); between-category deviant mean = −22.23 µv (9.31); $F(2, 38) = 9.66$, $p < .001$, $p_{\text{rep}} = .99$, $\eta_p^2 = .34$). There was no significant interaction of Stimulus and Electrode ($F(4.80, 91.10) = 0.35$, $p = .87$, $p_{\text{rep}} = 0.55$, $\eta_p^2 = .02$; Greenhouse-Geisser corrected). Paired samples *t*-tests (with Bonferonni corrected significance level of $p < .017$) showed that the between-category deviant differed from the standard ($t(19) = 3.69$, $p < .005$, $d = 1.04$), but the within-category deviant did not, ($t(19) = 1.72$, $p = .10$, $d = 0.42$). There was a significantly greater amplitude for the between- than within-category deviant, $t(19) = 3.45$, $p < .005$, $d = 0.71$.

3.1.2. NSW/PSW time range

As can be seen in Fig. 3, it appears that for C3, C4, and Pz, the between-category deviant elicited the largest NSW, and the amplitude for the standard and within-category deviant were similar. For Cz, both deviants appear to have greater negative amplitudes

Table 2
The mean amplitude (μv) of the averaged slow wave (SD) elicited by the standard (S), the within-category deviant (WD) and between-category deviant (BD) at each electrode (Cz, C4, C3, and Pz). The inferential statistics for significant differences in the amplitude of the standard and the between-category deviant (oddball effect), and in the amplitude of the between- and within-category deviants are given.

Electrode	S	WD	BD	S vs. BD (oddball effect)	BD vs. W
Cz	8.47 (18.90)	−4.87 (20.09)	−5.58 (18.53)	Not sig.	Not sig.
C4	−4.08 (18.49)	−4.72 (20.41)	−25.32 (19.57)	$t(19) = 3.40$, $p < .005$, $d = 1.12$	$t(19) = 3.53$, $p < .005$, $d = 1.03$
C3	10.71 (19.77)	8.75 (17.86)	−18.32 (18.90)	$t(19) = 5.42$, $p < .001$, $d = 1.50$	$t(19) = 6.60$, $p < .001$, $d = 1.47$
Pz	−6.18 (22.73)	−9.81 (16.48)	−25.92 (19.10)	$t(19) = 2.94$, $p < .01$, $d = 0.94$	$t(19) = 3.12$, $p < .01$, $d = 0.90$

than the standard, while at Fz there appear to be no differences among the stimuli. Statistical analysis generally supported these impressions. Two-way ANOVA identified a significant interaction between Stimulus and Electrode ($F(8, 152) = 2.99$, $p < .005$, $p_{\text{rep}} = 0.97$, $\eta_p^2 = .14$) so a series of one-way ANOVAs were conducted separately for each electrode with Stimulus as a factor. The mean amplitude of the slow wave was significantly different across stimuli for all electrodes (smallest $p < .05$), except at Fz ($F < 1$, $p > .05$). Table 2 gives the mean amplitude of the slow wave elicited by the standard and the within- and between-category deviants for electrodes where there were significant stimulus differences. The table also gives inferential statistics for significant paired samples *t*-tests (Bonferroni corrected significance level of $p < .017$) that compared the amplitude of the standard and the deviant for within- and between-category deviants separately, and that compared the amplitude of the within- and between-category deviants.

There were significant differences in mean amplitude for the standard and between-category deviant (an oddball effect) at C3, C4 and Pz (see Table 2 for statistics), but not at Cz, $t(19) = 0.34$, $p = 0.03$, $d = 0.75$. At C4 and Pz the slow wave for the between-category deviant was more negative than the slow wave for the standard, and at C3 while there was negativity for the between-category deviant slow wave there was positivity for the standard. There were no differences in mean amplitude for the standard and within-category deviant at any site (closest to significance was Cz, $t(19) = 2.02$, $p = .057$, $d = 0.68$; all others largest $t = 0.58$, smallest $p = .57$).

There was a significant difference in the mean amplitude of the slow wave for within- and between-category deviants at C3, C4 and Pz and (see Table 2), but not at Cz, $t(19) = 0.15$, $p = 0.89$, d = 0.04. At C4 and Pz the slow wave was more negative for the between- than within-category deviant. At C3, while there was negativity for the between-category deviant there was positivity for the within-category deviant.

3.1.3. Other time ranges

There were no stimulus differences for mean amplitude within the 100–250 ms time range, $F(2, 152) = 1.62$, $p = 0.21$, $p_{\text{rep}} = 0.72$, $\eta_p^2 = .08$. Stimulus differences were found however, for mean amplitude of the 650–1150 ms time range, ($F(2, 152) = 15.43$, $p < .001$, $p_{\text{rep}} = 0.99$, $\eta_p^2 = .45$), that followed an identical pattern to the stimulus differences for the Nc. As for the Nc, the between-category deviant differed from the standard ($t(19) = 6.00$, $p < .001$, $d = 1.95$), but the within-category did not ($t(19) = 2.27$, $p = .035$, $d = 0.74$), and there was a significantly greater amplitude for the between- than within-category deviant, ($t(19) = 3.01$, $p < .01$, d = 1.07).

3.2. Control task: removal of categorical context

Separate averages were computed for the green and blue stimuli (see Fig. 4). As can be seen in Fig. 4, it appears that at all electrodes, the amplitude of the Nc and the slow waves for the blue and green stimuli were similar.[5] Analyses were conducted as for the visual oddball task, with the exception that the factor of Stimulus had two levels (green/blue). There were no significant main effects of Stimulus or interactions between Stimulus and Electrode for either the Nc (largest $F = 0.26$, smallest $p = 0.91$) or the slow waves (largest $F = 0.21$, smallest $p = 0.93$). There were also no significant main effects of Stimulus or interactions between Stimulus and Electrode for the time ranges 100–250 ms (largest $F = 0.91$, smallest $p = 0.35$) or 650–1150 ms (largest $F = 0.57$, smallest $p = 0.46$). An analysis that selected trials from only the first 40% of trials (equivalent exposure for each stimulus relative to the visual oddball task) replicated the lack of significant difference in amplitude of the two stimuli across electrodes for the Nc (largest $F = 1.53$, smallest $p = 0.23$), slow wave (largest $F = 0.87$, smallest $p = 0.36$) and for 100–250 ms (largest $F = 0.95$, smallest $p = 0.34$) and 650–1150 ms (largest $F = 1.37$, smallest $p = 0.26$).

3.3. Behavioral post-test

Preference for the between-category deviant stimulus (2.5B) was significantly greater when the behavioral post-test followed the visual oddball task (mean preference = 58.16%, SD = 9.6) than when the behavioral post-test followed the control task (mean preference = 50.44%, SD = 8.57), $t(37) = 2.65$, $p < .05$, $d = 0.87$. Preference for this stimulus was significantly greater than chance (50%) following the visual oddball task, $t(19) = 3.80$, $p < .005$, d = 0.85, but not following the control task $t(18) = 0.22$, $p = .83$, $d = .05$, indicating that preference for the stimulus depended on the categorical context of the stimuli in the preceding task.

4. Discussion

On a visual oddball task, infant ERPs were recorded to infrequent deviant stimuli that were either from the same or different color category to a frequently presented standard stimulus. Analysis of stimulus differences within the Nc and NSW and PSW time ranges revealed differences that were consistent with color CP and categorical responding to color. First, the between-category deviant elicited a greater Nc than the within-category deviant, with an oddball effect (greater Nc for deviant than standard) for

---

[5] Comparison of the waveform morphology for the control task and the visual oddball task reveals differences: the Nc appears smaller, and there appears to be larger positive slow wave activity. Waveform morphology is affected by both the stimulus ratios and the degree of randomness in the stimulus presentation (see Ackles & Cook, 1998). It is possible that the less random and more repetitive stimulus presentation in the control than the visual oddball task led to lower thresholds for the formation of stimulus representations and facilitated updating in working memory – giving a larger PSW in the control than the visual oddball task. Due to this greater stimulus encoding and updating in working memory, stimuli in the control task may also have appeared less novel and required less attentional allocation – potentially explaining the smaller Nc in the control task. We consider there to be a strong PSW in the control task, rather than artifactual slow drift, as there is no slow drift in the baseline (−100 to 0 ms) or in the Nc. The PSW is of comparable amplitude to the PSW in another study that employed an alternating 50:50 design and that tested infants of a similar age (e.g., Ackles & Cook, 1998).

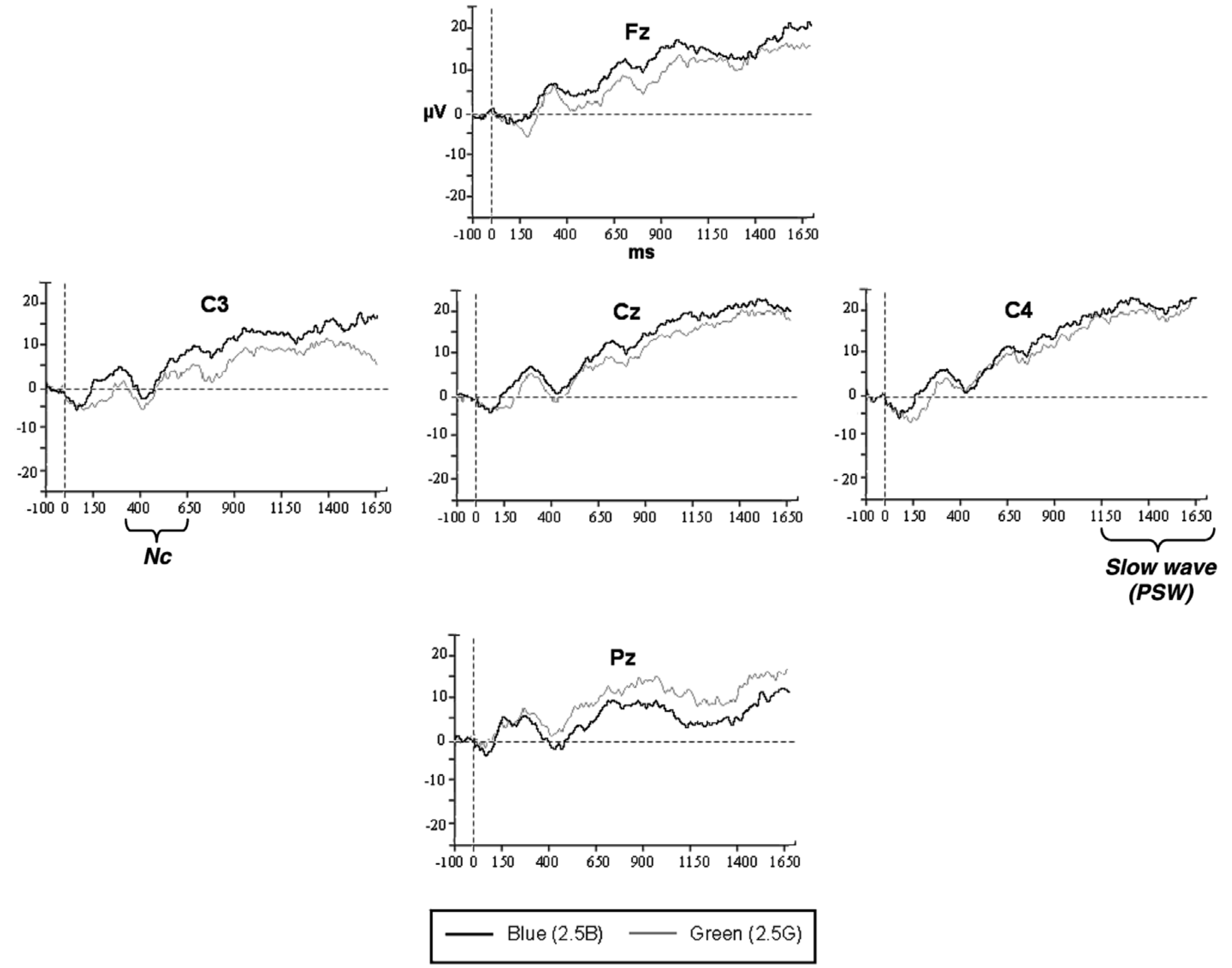

Fig. 4. Grand-averaged ERP waveforms elicited during the 1,700 ms following stimulus onset (0 ms) in response to blue (black lines), and green (gray lines) stimuli when presented alternately in the absence of the standard. The Nc is indicated for electrode C3, and the slow wave (PSW) is indicated for electrode C4.

the between- but not within-category deviant. Second, within the slow wave time range, there were differences in the amplitude and latitude of the slow waves elicited by the stimuli. At several sites, the between-category deviant elicited a greater NSW than the within-category deviant and the standard, and at two central sites the slow wave for the standard or the within-category deviant was actually positive. There was no difference in amplitude of slow waves elicited by the standard and the within-category deviant. Importantly, on a control task where ERPs were recorded to alternations of the two stimuli that were the within- and between-category deviants in the visual oddball task, there were no differences in the ERP components elicited by the two stimuli, indicating a similar amount of attentional allocation (Nc) and stimulus updating and encoding in working memory (PSW) for the two stimuli when categorical context is removed. Following the visual oddball task there was a preference for the between-category deviant, but there was no preference for this stimulus following the control task, suggesting that the preference was dependent on the categorical context of the stimulus on the preceding task.

These findings reveal, for the first time, the electrophysiological markers of color CP in infancy. One interpretation of these effects is that, within the context of frequent repetition of a color, a different-category color receives greater attentional allocation (Nc) and is more novel (NSW) than a same-category color. Additionally, consistent with the novelty preference studies of infant categorical perception of color, the same-category color receives no more attentional allocation and is equally novel as the frequently repeated color.

The current investigation contributes to a greater understanding of the neural markers of categorical responding in infancy. There have only been a few previous ERP studies of categorical effects in infancy: one for CP of phonemes in 3-month old infants (Dehaene-Lambertz & Baillett, 1998) and two for category learning at 6-months (Grossman et al., in press; Quinn et al., 2006). In Quinn et al.'s investigation, ERPs were recorded while infants viewed a series of cat images during category training (familiarization period) and novel cat and dog stimuli during a test period. Category effects were found for the Nc and the slow waves. For example, the Nc was greatest for the novel-category stimuli (dogs) during the test period, and the NSW indicated grouping of same-category exemplars presented in the second half of familiarization and test. It was argued that the Nc could be a marker for novel-category preference (between-category dissimilarity) and the NSW for same-category equivalence (within-category similarity), and that different mechanisms underlie these two computations, with within-category similarity being a later more complex computation.

Grossman et al. (in press) used a similar approach to assess category learning of basic-level categories (bird vs. fish) and global level categories (birds vs. cars). As for Quinn et al., during the test period, novel-category stimuli elicited an enhanced Nc relative to the familiar category. Additionally, during the test period, familiar-category stimuli elicited a PSW, yet there was a return to baseline for novel-category stimuli. These category effects were found in anterior regions. In contrast, an early positive component in posterior regions appeared sensitive to repetition of individual exemplars within a category (within-category discrimination).

The current investigation confirms that category effects for the Nc and the slow waves generalize to other types of categories (color) and categorical responding (CP). Despite the different type of categorization and the different design and procedure of the current investigation compared to Quinn et al. (2006) and Grossman et al. (in press), there are several similarities in the pattern of category effects for the Nc and slow waves. First, all three studies found an enhanced Nc for stimuli that were from a different category to the familiarized or standard context (the novel-category stimuli in Quinn et al. and Grossmann et al., and the between-category deviant in the current investigation). Second, both the current investigation and Grossmann et al., found that stimuli that were from the same category to the familiarized category or the standard context (the familiar-category stimuli in Grossmann et al. and the within-category deviant at two sites in the current investigation) elicited a PSW. Grossmann et al. suggest that the PSW for new familiar-category stimuli could indicate the incorporation of the new stimulus into the existing familiar category representation. This interpretation could also be applied to the current investigation – the PSW for the within-category deviant may indicate that the stimulus is being incorporated into the representation of the category of the standard and that category representations are being updated. Third, both the current investigation and Quinn et al. find same-category equivalence for the slow waves (equivalent NSW for same-category exemplars in Quinn et al., and equivalent slow waves for the standard and the within-category deviant in the current investigation). The current investigation however, finds that both within-category similarity (equivalent amplitude for within-category deviant and standard) and between-category dissimilarity (greater amplitude for between-category than within-category deviant) are reflected in the slow waves as well as the Nc. Therefore, it appears that at least for categorical perception of color, similar mechanisms underpin the identification of a deviant color as belonging to the same or to a different category than the standard context.

In the current study, category effects were present for the Nc, but there were no category effects during an earlier time range at the sites we analyzed. This potentially suggests that infants first register the categorical status of a color during an attentional phase of processing between 250 and 600 ms of stimulus onset. Dehaene-Lambertz and Baillet's (1998) ERP investigation of CP of phonemes at 3-months find that category effects for phonemes first appear around 400–480 ms. The infant heard four syllables on each trial, with the fourth syllable either from the same phonetic category (within-category) or from a different phonetic category (between-category) as the previous syllables. At frontal sites, a positive ERP component during the 400–480 ms time range had greater amplitude for the between-category compared to within-category syllable, and there was equivalent amplitude for within-category and control conditions. The similarity of the time course for infant CP of phonemes in Dehaene-Lambertz and Baillet's investigation and for infant CP of color in the current study may indicate a similar categorical mechanism for infant CP across different perceptual domains. The lack of category effects, in both investigations, during the first couple of 100 ms after stimulus onset is in contrast to ERP studies of CP in adults, where category effects have been found in early visual ERP components (e.g., P1) as early as 90 ms (e.g., Holmes et al., 2009). This may indicate that infant CP depends more on attentional mechanisms than early perceptual ones. However, caution is required here as it is possible that earlier category effects (e.g., for the P1 component) are present at occipital regions that were not analyzed here. Whether or not there are earlier category effects at occipital regions awaits further investigation.

Electrophysiological evidence of color category effects in infants has implications for the debate about how color categories form in language and cognition. There is converging evidence that color CP in adults is dependent on language, for example that it varies cross-culturally (e.g., Roberson, Davies, & Davidoff, 2000), that it has a LH bias (Drivonikou et al., 2007; Gilbert, Regier, Kay, & Ivry, 2005) and that a network of brain areas involving linguistic processing is likely to be involved in color judgments (Tan et al., 2008). In the light of all the evidence for language dependent color CP, it has been somewhat surprising that pre-linguistic infants respond categorically to color on behavioral tasks (Bornstein et al., 1976; Catherwood et al., 1987, 1990; Franklin & Davies, 2004; Franklin et al., 2005; Franklin et al., 2008). Some have questioned whether the effect is restricted to certain stimuli, tasks or measures, and there has been some skepticism of the reliability of the effect, with the importance of replication emphasized (Davidoff, Goldstein, & Roberson, 2009). Others have been skeptical of infant color category effects on behavioral measures such as novelty preference, questioning the underlying mechanisms of such measures (Özgen, 2004). It is therefore important that converging evidence for a categorical response to color in infancy is provided using different stimulus sets, approaches and measures. The current study, by using an electrophysiological measure, provides compelling evidence to strengthen the case that color CP can occur without language, while also providing further information about the time course and underlying mechanisms of the effect.

The converging evidence for a categorical response to color in infants strongly suggests that color categories are not entirely linguistically constructed. Developmental behavioral studies suggest that pre-linguistic CP is lateralized to the RH, and that lateralization switches to the LH around the time that the words for the relevant categories are learnt (Franklin et al., 2008). One hypothesis is that there is a RH substrate for a categorical response to color that is replaced or suppressed by the mechanisms of language once color terms are learned (Franklin et al., 2008). The current investigation, due to the use of low density ERP and non-lateralized stimulus presentations, does not allow for confirmation of the RH bias in infant color CP. However, the current investigation does establish an approach that, if combined with high-density ERP recording, could further test for changes in the lateralization of color CP across development.

Further research is also needed to understand the relationship between the categorical response to color in infants and color categories in language. Despite variation in how the world's languages categorize the color spectrum, it does appear that there are statistical tendencies for color categories to form at certain points in the color space, with universal constraints on color categorization (Kay & Regier, 2003; Regier et al., 2005, 2007). It is possible that color categorization in infancy provides these constraints, or that infant color categories and color categories in language, partly originate from a common source. For example, some have suggested that color categories in language are acquired from sensitivity to statistical tendencies in the color of surfaces in our environment (Yendrikhovskij, 2001), the shape of perceptual color space (Jameson & D'Andrade, 1997; Regier et al., 2007), and properties of ambient light sources (Shepard, 1992). Both color categories in language and infant color categories could be acquired through mechanisms such as these. We do not argue here that infant color categories are necessarily 'hardwired'.

The current investigation provides the first electrophysiological evidence for a categorical response to color before color terms are acquired. By recording ERPs on a visual oddball task, category effects are found for several infant ERP components. The study identifies similarity in the neural markers for different types of categorical responding in infancy, and also identifies a similar time course for color CP compared to phoneme CP in infancy. The findings therefore have implications both for our understanding of the processes that underlie categorical responding in infancy, and for our understanding of how categories form in color language and cognition.

Acknowledgments

Research was supported by a Joint Innovation grant to Anna Franklin, Amanda Holmes and Ian Davies and a departmental Ph.D. bursary to Alexandra Clifford. We thank Laura Bevis, Justine Cornforth, Gilda Drivonikou and Jacqueline Hood for infant testing assistance, and Alex Hogan for advice on infant EEG. We are grateful to the infants and their parents.

References

Ackles, P. K., & Cook, K. G. (1998). Stimulus probability and event-related potentials of the brain in 6-month-old human infants: A parametric study. *International Journal of Psychophysiology, 29*, 115–143.

Ackles, P. K., & Cook, K. G. (2007). Attention or memory? Effects of familiarity and novelty on the Nc component of event-related brain potentials in six-month-old infants. *International Journal of Neuroscience, 117*, 837–867.

Berlin, B., & Kay, P. (1969). *Basic color terms: Their universality and evolution*. Berkeley: University of California Press.

Bornstein, M. H. (2006). Hue categorization and color naming: Physics to sensation to perception. In N. J. Pitchford & C. P. Biggam (Eds.), *Progress in colour studies. Psychological aspects* (Vol. II, pp. 35–68). Amsterdam/Philadelphia: John Benjamins.

Bornstein, M. H. (2008). Hue categorization and color naming: Cognition to language to culture. In R. M. MacLaury, G. V. Paramei, & D. Dedrick (Eds.), *Anthropology of colour: Interdisciplinary multilevel modeling* (pp. 3–27). Amsterdam/Philadelphia: John Benjamins.

Bornstein, M., Kessen, W., & Weiskopf, S. (1976). Color vision and hue categorisation in young human infants. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 115–129.

Bornstein, M., & Korda, N. (1984). Discrimination and matching within and between hues measured by reaction times: Some implications for categorical perception and levels of information processing. *Psychological Research, 46*, 207–222.

Catherwood, D., Crassini, B., & Freiberg, K. (1987). The nature of infant memory for hue. *British Journal of Developmental Psychology, 5*, 385–394.

Catherwood, D., Crassini, B., & Freiberg, K. (1990). The course of infant memory for hue. *Australian Journal of Psychology, 42*, 277–285.

Davidoff, J., Goldstein, J., & Roberson, D. (2009). Nature versus nature: The simple contrast. *Journal of Experimental Child Psychology, 102*, 246–250.

DeBoer, T., Scott, L. S., & Nelson, C. A. (2004). In T. C. Handy (Ed.), *Event-related potentials: A methods handbook* (pp. 263–297). Cambridge, MA: MIT Press.

de Haan, M., & Nelson, C. A. (1997). Recognition of the mother's face by six-month-old infants: A neurobehavioral study. *Child Development, 68*, 187–210.

Dehaene-Lambertz, G., & Baillett, S. (1998). A phonological representation in the infant brain. *NeuroReport, 9*, 1885–1888.

Drivonikou, G. V., Kay, P., Regier, T., Ivry, R. B., Gilbert, A. L., Franklin, A., et al. (2007). Further evidence for lateralization of Whorfian effects to the right visual field. *Proceedings of the National Academy of Sciences, 104*, 1097–1102.

Franklin, A., & Davies, I. R. L. (2004). New evidence for infant colour categories. *British Journal of Developmental Psychology, 22*, 349–377.

Franklin, A., Drivonikou, G. V., Bevis, L., Davies, I. R. L., Kay, P., & Regier, T. (2008). Categorical Perception of color is lateralized to the right hemisphere in infants, but to the left hemisphere in adults. *Proceedings of the National Academy of Sciences, 105*, 3221–3225.

Franklin, A., Pilling, M., & Davies, I. R. L. (2005). The nature of infant colour categorisation: Evidence from eye-movements on a target detection task. *Journal of Experimental Child Psychology, 91*, 227–248.

Gilbert, A. L., Regier, T., Kay, P., & Ivry, R. B. (2005). Whorf hypothesis is supported in the right visual field but not the left. *Proceedings of the National Academy of Sciences, 103*, 489–494.

Grossman, T., Gliga, T., Johnson, M. H. & Mareschal, D. (in press). The neural basis of perceptual category learning in human infants. Journal of Cognitive Neuroscience.

Harnad, S. (1987). Psychophysical and cognitive aspects of categorical perception: A critical overview. In S. Harnad (Ed.), *Categorical perception: The groundwork of cognition* (pp. 287–301). New York: Cambridge University Press.

Holmes, A., Franklin, A., Clifford, A., & Davies, I. R. L. (2009). Neurophysiological evidence for categorical perception of color. *Brain and Cognition, 69*, 426–434.

Jameson, K. A., & D'Andrade, R. G. (1997). It's not really red, green, yellow, blue: An inquiry into perceptual color space. In C. L. Hardin & L. Maffi (Eds.), *Color categories in thought and language* (pp. 295–319). Cambridge: Cambridge University Press.

Jasper, H. (1958). The 10–20 electrode system of the international federation. *Electroencephalography and Clinical Neurophysiology, 10*, 371–375.

Kay, P. (2005). Color categories are not arbitrary. *Cross Cultural Research, 39*, 39–55.

Kay, P., & Regier, T. (2003). Resolving the question of color naming universals. *Proceedings of the National Academy of Sciences, 100*, 9085–9089.

Knoblauch, K., Vital-Durand, F., & Barbur, J. L. (2001). Variation of chromatic sensitivity across the life span. *Vision Research, 41*, 23–36.

Lieberman, A. M., Harris, K. S., Hoffman, H. S., & Griffith, B. C. (1957). The discrimination of speech sounds within and across phoneme boundaries. *Journal of Experimental Psychology, 54*, 358–368.

MacLaury, R. M., Paramei, G. V., & Dedrick, D. (2008). *Anthropology of colour: Interdisciplinary multilevel modeling*. Amsterdam/Philadelphia: John Benjamins.

Mareschal, D., & Quinn, P. C. (2001). Categorization in infancy. *Trends in Cognitive Sciences, 5*, 443–450.

Nelson, C. A., & Monk, L. S. (2001). The use of event-related-potentials in the study of cognitive development. In C. A. Nelson & M. Luciana (Eds.), *Developmental cognitive neuroscience* (pp. 125–136). Cambridge: MIT Press.

Newhall, S. M., Nickerson, D., & Judd, D. B. (1943). Final Report of the O.S.A subcommittee on the spacing of Munsell colors. *Journal of the Optical Society of America, 33*, 385–418.

Özgen, E. (2004). Language, learning and color perception. *Current Directions in Psychological Science, 13*, 95–98.

Pereverzeva, M., Chien, S. H.-L., Palmer, J., & Teller, D. Y. (2002). Infant photometry: Are mean adult isoluminance values a sufficient approximation to individual infant values? *Vision Research, 42*, 1639–1649.

Quinn, P., Westerlund, A., & Nelson, C. A. (2006). Neural markers of categorization in 6-month-old infants. *Psychological Science, 17*, 59–66.

Regier, T., Kay, P., & Cook, R. S. (2005). Focal colors are universal after all. *Proceedings of the National Academy of Sciences, 102*, 8386–8391.

Regier, T., Kay, P., & Khetarpal, N. (2007). Color naming reflects optimal partitions of color space. *Proceedings of the National Academy of Sciences, 104*, 1436–1441.

Reynolds, G. D., & Richards, J. E. (2005). Familiarization, attention, and recognition memory in infancy: An ERP and cortical source localization study. *Developmental Psychology, 41*, 598–615.

Richards, J. E. (2003). Attention affects the recognition of briefly presented stimuli in infants: An ERP study. *Developmental Science, 6*, 312–328.

Roberson, D., Davies, I. R. L., & Davidoff, J. (2000). Color categories are not universal: Replications and new evidence from a stone-age culture. *Journal of Experimental Psychology: General, 129*, 369–398.

Shepard, R. N. (1992). The perceptual organization of colors: An adaptation to the regularities of the terrestrial world. In J. Barkow, L. Cosmides, & J. Tooby (Eds.), *The adapted mind* (pp. 494–532). Oxford, UK: Oxford University Press.

Tan, L. H., Chan, A. H. D., Kay, P., Khong, P.-L., Yip, L. K. C., & Luke, K.-K. (2008). Language affects patterns of brain activation associated with perceptual decision. *Proceedings of the National Academy of Sciences, 105*, 4004–4009.

Yendrikhovskij, S. N. (2001). Computing color categories from statistics of natural images. *Journal of Imaging Science and Technology, 45*, 409–418.