



Chromaticity separation and the alpha response

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ABSTRACT

Chromatic gratings can be uncomfortable to view and can evoke a large haemodynamic response. Both the discomfort and the amplitude of the haemodynamic response increase monotonically with the perceptual difference in the colour of the component bars of the grating, as registered by the separation in their chromaticity in the CIE 1976 UCS diagram. Individuals with photosensitive epilepsy exhibit epileptiform EEG activity in response to flickering light of alternate colours. The probability of the epileptiform response again increases monotonically with the separation of the colours in the CIE UCS diagram. We investigated whether alpha power, which is known to reflect the excitation of large populations of neurons, is similarly affected by the separation in chromaticity. Chromatic square-wave gratings with bars that differed in CIE UCS chromaticity were presented, together with a central fixation cross. In 18 non-clinical participants, alpha responses were recorded over the visual cortex (O1, Oz, O2, PO3, POz, PO4, P1, P2) and compared to responses in prefrontal cortex (F1, F2). Gratings comprised bars of two alternate colours that either had a small difference in chromaticity (mean CIE UCS separation of 0.03), a medium difference (mean separation of 0.19), or a large difference (mean separation of 0.43). The colour pairs had chromaticities that lay on the red-green, red-blue, or blue-green borders of the screen gamut. Regardless of the hue, the larger the separation in chromaticity, the greater the alpha desynchronization and the lower the alpha power ($p = 0.004$), but only in posterior electrodes ($p < 0.001$). Together this indicates that differences in colour evoke a cortical excitation that increases monotonically with the colour difference. In this respect the alpha response resembles the haemodynamic response.

1. Introduction

Discomfort from visual stimuli can be largely accounted for by the parameters of the stimulus (Penacchio and Wilkins, 2015). Uncomfortable images contain high contrast energy at mid-range spatial frequencies (Fernandez and Wilkins, 2008). One example of a high-energy image is a block of text, which comprises high contrast stripes (Wilkins and Nimmo-Smith, 1987). Achromatic mid-range spatial frequency gratings (stripes) produce a larger fMRI BOLD response compared to low or high spatial frequencies, particularly in individuals with migraine (Huang et al., 2003). Mid-range spatial frequencies are known to be epileptogenic, evoke visual illusions (Wilkins et al., 1984), and be uncomfortable to view, especially so for individuals with migraine (Marcus and Soso, 1989; Haigh et al., 2012). However, the contribution of colour to visual discomfort is often overlooked.

The majority of studies investigating the adverse effects of colour have focused on the link between chromatic flicker and seizures in patients with photosensitive epilepsy. During a television episode of Pokémon aired in 1997 in Japan, about 700 adults and children were hospitalised with seizures after the background of one of the scenes

alternated between red and blue at a frequency of 12.5 Hz for 4 s. It was already known that achromatic flicker could cause seizures in patients with photosensitive epilepsy (Harding and Jeavons, 1994; Binnie, Findlay and Wilkins, 1985), but the effects of chromatic flicker were largely unknown. Many of the original studies, some preceding the Pokémon incident had identified red flicker as the most likely to induce a photoparoxysmal response (PPR) (e.g. Takahashi and Tsukahara, 1998). Parra, Lopes da Silva, Stroink and Kalitzin (2007) however, found that it was specifically the alternating red-blue flicker that produced more PPRs than other colour mixtures at low (~10 Hz) frequencies. Bhagat et al. (2009) also found that the red-blue flicker (closely followed by the red-green flicker) produced more PPRs than blue-green flicker. However, it may not be the colour per se that causes the discomfort, but the chromatic contrast in the flicker. Red-blue colours may have a larger chromaticity separation than blue-green.

To measure systematically the effect of chromatic contrast on visual discomfort, Haigh et al. (2013) obtained ratings of discomfort from horizontal gratings with stripes of alternate colours of similar luminance. They found that regardless of the specific colour-pair used, there was a monotonic increase in discomfort with the separation in

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chromaticity. Similarly, there was a monotonic increase in the amplitude of the NIRS oxyhaemoglobin response as a function of the separation in chromaticity. These relationships were most evident when using the Commission Internationale de L'éclairage (CIE) Uniform Chromaticity Scale diagram (UCS) 1976, which is a chromaticity diagram that maximises perceptual uniformity. There was no significant relationship with discomfort or haemodynamic response when colour difference was calculated according to cone activation without adjustment for perceptual colour difference (e.g. by adjustment of the S/(L + M) coordinate in MacLeod-Boynton colour space). Although the stimuli presented by Haigh et al. (2013) varied chromaticity across spatial patterns, and the studies in photosensitive epilepsy varied chromaticity in time as flicker, individuals with photosensitive epilepsy who are sensitive to flicker are also sensitive to grating patterns (Wilkins et al., 1975, 1979). Together this suggests that the separation of chromaticity may contribute both to visual discomfort, and to the photoparoxysmal activity in patients with photosensitive epilepsy.

The visual discomfort from images has been thought to be evoked as a result of excitability within the visual cortex (Bargary et al., 2015), and hence those individual with a hyper-excitability cortex are more sensitive to these stimuli (e.g. individuals with photosensitive epilepsy or migraine). The larger metabolic responses to uncomfortable images suggest a greater neural excitation. Although the metabolic response is an indirect measure of neural activity, it is associated with changes in more direct measures. The electroencephalogram (EEG) measures the electrical changes produced by large populations of neurons, and EEG responses, in particular the alpha response (8–12 Hz), have been associated with changes in metabolic response (Singh et al., 2003; Zumer et al., 2010; Brookes et al., 2005). Singh et al. (2003) was one of the first to find that areas of the cortex that showed an increase in fMRI signal, also showed event-related desynchronization in the alpha band (which is a measure of alpha suppression). Mayhew et al. (2013) found that the fluctuations in the alpha response could explain some of the variance in the BOLD response. Furthermore, visual stimuli that were presented during the trough of the alpha wave produced a larger BOLD response compared to stimuli presented during the peak of the alpha wave, suggesting that the alpha response is closely related to cortical excitability (Scheeringa et al., 2011).

In the current study, we used the same stimuli as reported by Haigh et al. (2013) to measure the alpha response, which includes stimuli that are known to be uncomfortable to view and evoke a large haemodynamic response. We recorded the EEG in response to chromatic square-wave gratings that were photometrically similar in their overall luminance and varied with respect to the separation between the chromaticities of the component bars. It was expected that the larger the chromaticity separation, the greater the alpha suppression.

2. Materials and methods

2.1. Participants

Nineteen females and three males from the University of Essex participated in the study; mean age 21.2 (range 18–54). All had a minimum of 6/6 visual acuity (Lighthouse Test for Near and Far Visual Acuity), a minimum stereo acuity of 60 sarc (Titmus test; Stereo Optical Co. In., Chicago, IL, USA), and showed no red-green colour deficiencies (Ishihara plates). This study complied with the Code of Ethics of the World Medical Association (Declaration of Helsinki), and was approved by the University of Essex Review Board. All participants gave their informed consent.

2.2. Apparatus

The stimuli were displayed on a 24" LCD Dell screen with a backlight refresh rate of 162.5 Hz. The screen was powered by a Mac G4 Powerbook.

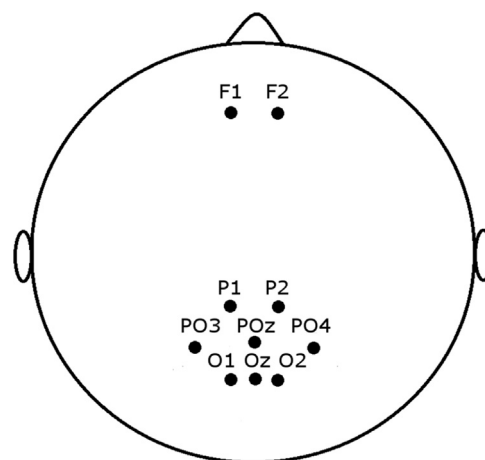


Fig. 1. Placement of electrodes used. The anterior channels (F1 and F2) were used as control channels to test for systemic effects of the stimuli, compared to the posterior channels (P1, P2, PO3, POz, PO4, O1, Oz, and O2) that would indicate local (visual) effects.

The electrophysiological response was measured using a NeuroScan SynAmps RT system (Compumedics USA Inc, Charlotte, NC, USA), and analysed using NeuroScan Scan 4.5 (Compumedics, Melbourne, Australia). Impedances for all electrodes were reduced to below 15 kOhm before the start of each session. All data were continuously sampled at 1000 Hz with a bandpass filter of 0.1–200 Hz and a 50 Hz notch filter. Online, EEG data were referenced to the left mastoid, and grounded at FPz. The electrode placement is shown in Fig. 1 with the labels appropriate for the 10–20 system for electrode placement. Four electrodes were placed around the eyes to record blinks and eye movement. One electrode was placed above the left eye, and another below the left eye. One electrode was placed on the outer canthus of the left eye and another was placed on the outer canthus of the right eye.

2.3. Stimuli

Gratings were displayed using SuperLab version 4.0.7b. To select the chromaticities, the three extremes of the screen gamut (red only, green only and blue only pixels) were measured using a tele-spectroradiometer (model PR-670[®], Photo Research[®], Chatsworth, CA, USA). The midpoints (29 cd/m²) between each of the three extremes that had similar photometric luminance were calculated. Chromaticities equidistant from either side of the midpoint were then used in alternating stripes to create red-green (RG), green-blue (GB) and red-blue (RB) grating patterns. The spatial frequency of the patterns was 2cpd at a viewing distance of 1 m. Three colour pairs were created for each gamut extreme: a small separation of chromaticities in the CIE UCS 1976 diagram (mean separation of the chromaticities = 0.03), a medium separation (mean separation of the chromaticities = 0.19) and a large separation (mean separation of the chromaticities = 0.43). See Table 1 for CIE UCS co-ordinates. The gratings were circular in outline, subtended 10 deg, and were surrounded by a grey field of similar luminance ($u' = 0.192$, $v' = 0.475$, $Y = 35.3$). A central black fixation cross was shown throughout the trial (subtending 1.3 degrees of visual angle; example shown in Fig. 2. Stimuli available as tiff files in Supplementary material).

2.4. Procedure

Each stimulus was presented for 1 s followed by a grey screen lasting 1 s, and this pair of stimuli was presented 8 times. There were sufficient stimulus repetitions to record a reliable alpha response. The 16 s presentation was then followed by a grey screen which lasted for an interval that varied randomly between 27 and 36 s with a uniform

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