Color and spatial frequency are related to visual pattern sensitivity in migraine.

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Abbreviations: VA–migraine with visual aura; MO–migraine without aura; L, M and S cone–long, medium and short wavelength sensitive cones; cpd–cycles per degree; Y–luminance; cd m^{-2}–candelas per metre squared; GII–general illusion index; CLCG–Cambridge low contrast gratings; MB (r,b) co-ordinates–Macleod-Boynton (1979) chromaticity co-ordinates; VTI–visual trigger index.

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ABSTRACT

Objective: To assess the potential for particular colors to alleviate visual discomfort when people with migraine view repetitive geometric or striped patterns.

Background: Visual stimuli, such as flicker, glare, or stripes, can trigger migraine and headache. They can also elicit feelings of discomfort and aversion. There are reports that color can be used to decrease the experience of discomfort and reduce migraine frequency.

Design/Methods: Five sets of striped patterns (3, 12 cpd) were created using cardinal colors tailored to selectively stimulate the early visual pathways: achromatic (black/white); tritan (black/purple, black/yellow); protan/deutan (black/red, black/green). All had the same high luminance contrast (0.9 Michelson contrast). Twenty-eight migraine (14 VA, 14 MO) and 14 control participants rated the discomfort and described the distortions seen in these patterns. They were also assessed for visual migraine/ headache triggers, contrast sensitivity, color vision, acuity, stereopsis, visual discomfort from reading and dyslexia.

Results: In the migraine groups, a comparable number of illusions were seen with the 3 and 12 cpd achromatic gratings, whereas in the control group the greatest number was seen with the 3 cpd grating. In the migraine groups only, all four colors reduced, to some extent, the number of illusions and two decreased the discomfort, particularly for the 12 cpd gratings. There were significant group differences for contrast sensitivity, reported visual migraine/headache triggers, and the visual discomfort scale. There were a few significant correlations between the different measures, notably between the achromatic visual discomfort measures and reports of visual migraine triggers.

Conclusions: Color, independent of luminance or particular color contrasts, can have therapeutic effects for people with visually triggered migraine as it can reduce the number of perceived illusions when viewing stripes or text. The effect was not color specific and was greatest for the 12 cycles per degree gratings. Given the significant associations between the achromatic discomfort measures and reports of visual triggers, and the lack of significant associations between the chromatic discomfort measures and reports of visual triggers, further research is recommended to explore the potential to reduce the number of visually triggered migraines with color in addition to alleviating visual discomfort.

INTRODUCTION

There are numerous anecdotal reports that features of the environment can reliably provoke migraine and other headaches. Research in this area is, however, limited by practical and ethical reasons. Consequently, much of the existing research on environmental migraine and headache triggers has been based on retrospective self-report questionnaires. Reported environmental triggers include visual stimuli, some of which are similar to those that can induce seizures in photosensitive epilepsy, such as flicker and repetitive geometric patterns, for example, stripes[1-6]. There is also an association between those who report that visual stimuli can act as migraine or headache triggers and the experience of visual discomfort, sometimes also referred to as pattern sensitivity, pattern glare or visual stress: those susceptible to visual triggers experience greater discomfort when viewing the trigger stimuli than those who do not[3-6]. They may also see the trigger stimuli distort and experience illusions of shape, motion or color. In this study, the associations between reports of visual triggers and two measures of visual discomfort were explored. Participants rated the discomfort and described the visual distortions they experienced when viewing both achromatic and chromatic striped patterns. They also completed a visual discomfort questionnaire[7].

Many other factors have also been cited as migraine triggers, commonly: stress, hormonal factors in women, hunger, disturbed sleep, odours and several foods and drinks (chocolate, cheese, citrus, red wine)[8,9]. Some reviews of the literature that have addressed light and visual stimuli as migraine triggers, however, have suggested that they are of similar importance to triggers such as stress and hormonal factors[2,5,6]. For example, Debney[2] noted that, in a sample of 344 migraine patients, 62% had "glare" as a precipitating factor, 53% had "flicker" and just 1% had "color" . Shepherd[5,6] asked participants to complete a questionnaire on migraine and headache triggers that included visual items. From the responses of 180 participants[6], at least one visual item was reported as a trigger in 60% of the migraine group and in 15% of the control group. In addition to stripes and flicker, other

cited visual triggers included glare, sunshine, bright reflections, abrupt transitions from dark to light, driving at night with oncoming car headlights, computer screens, reading, television and cinema.

There are reports of interventions that can reduce visual discomfort, which may have implications for understanding how to alleviate visually induced migraine or headaches. For example, visual discomfort has been reported to be reduced following successful prophylactic treatment with beta-blockers, but only in those patients whose migraine frequency and severity were improved with treatment[10]. Furthermore, the patients with the greatest visual discomfort when viewing striped patterns, prior to treatment, were those who responded most successfully to the beta-blockers. As a second example, visual discomfort has been reported to be reduced with the use of color, such as covering the uncomfortable visual stimuli or displays with a colored overlay, wearing tinted glasses, or using colored computer screen backgrounds[3,5,11-14]. It has also been suggested that the use of colored visual aids can result in a slight reduction in migraine frequency[13]. The mechanisms involved in the reduction of visual discomfort or migraine frequency with color are, however, unclear. In this study, the effect of repeated exposure to geometric patterns was assessed with achromatic black on white striped patterns and with striped patterns on four colored backgrounds to try to assess the potential for particular colors to alleviate visual discomfort and pattern glare.

Most of the previous research on alleviating visual discomfort with color has used a subjective method to select the optimum color[11-14]. Typically, participants are asked to read text, or view geometric patterns such as stripes, while a series of colors are added to the visual displays via tinted illumination, overlays, glasses or backgrounds. Participants are then asked about the comfort and clarity of the display or are given a reading task (a set text of common words presented in a nonsensical order) and completion time is recorded. The available colors are not, however, selected with any consideration of the organisation of the visual system's physiology. Instead, the colors for professionally prescribed tinted glasses

depend on the mixture of three primary colored lights in a light box, and overlay sets present colors that are approximately equally spaced in one of the CIE color spaces (the CIE Uniform Chromaticity Diagram, 1976). Luminance or luminance contrast is not necessarily held constant with either of these methods, however, so luminance and color may co-vary making it difficult to interpret performance changes with different colors. Indeed, a perplexing feature of the results to date is that the colors selected to reduce discomfort, provide optimum clarity, or improve reading speed, are idiosyncratic and vary greatly from individual to individual[13].

In the early visual pathways, color perception begins with the absorption of light by one or more of the three cone photoreceptors: the long- (L), middle- (M), and short- (S) wavelength sensitive cones (broadly, red, green and blue). These signals are transformed, within the retina, into two cone-opponent channels: L±M (loosely, red-green) and S-(L+M) (loosely, blue-yellow)[15-20]. Cone opponency continues in the retinofugal visual pathways until at least the primary visual cortex (V1)[19,20].

This two-pathway cone-opponent organisation in the early visual pathways results in two physiologically important sets of colors in any color space. They are the "cardinal" color directions as they stimulate one and only one cone-opponent pathway that connects the retina and cortex[16]. One cardinal direction comprises "tritan" colors that can be discriminated only by the differential signals from the S-cones. When neutral (grey or white) is included in such a set of colors, the appearance of the others varies from a pinkish purple, through the neutral, to a mustard yellow. The L– and M–cones respond to each of these colors, but their responses to the purples are identical to their responses to the neutral and to the yellows: the L- and M-cones cannot distinguish amongst these different colors. The second cardinal color direction is defined by colors that can be discriminated only by the L- and M-cones. When a neutral is included in such a set of colors, the appearance of the other colors varies from a saturated pink, through the neutral, to a bluish green. This time, the S-cones have a

response to each of these colors, but they cannot discriminate amongst them since their responses to the pinks are identical to their responses to the neutral and to the greens. These colors can only be discriminated because of the differential responses they elicit in the L- and M-cones.

Here, five sets of striped patterns were created to assess the effects of color on visual discomfort/pattern sensitivity in migraine and control groups, using cardinal colors that selectively stimulate the early visual pathways: achromatic (black and white/neutral stripes); +S (black and purple stripes); –S (black and yellow stripes; +L(–M) (black and pink/red stripes); –L(+M) (black and green stripes). Recent research using near infra-red spectroscopy and fMRI has suggested the optimal color that reduces discomfort does so by changing both striate and extrastriate cortical activation[21], although the authors could only speculate on the reasons for the wide range of optimum colors selected by different participants. In fact, any pre-cortical contribution to the effects of color on visual discomfort/pattern sensitivity has not been addressed to date, yet anomalous activity in the pre-cortical pathways may make a significant contribution as has been shown for various other visual tasks[22-24]. Cardinal colors were, therefore, selected to seek out evidence for any pre-cortical contribution to the alleviation of visual discomfort/pattern sensitivity with the use of color. Finally, the visual discomfort questionnaire[7] addresses discomfort and distortions experienced while reading text, which are stripes on a page. This questionnaire was included to provide an additional measure of discomfort in a stimulus that is frequently encountered in day to day life.

METHOD

Participants

Twenty-eight migraine (14 VA, 14 MO) and fourteen control participants were recruited (Table 1). All participants completed a questionnaire detailing the characteristics of their

headaches. All migraine participants fulfilled the IHS classification for migraine with (VA) or without (MO) visual aura[25]. None of the control participants had headaches fulfilling the IHS criteria and none had a history of frequent or severe headaches. The headaches reported by the control group were consistent with episodic tension type headache, sinus headache, and dehydration (the study was conducted in summer in Australia). All participants had a binocular visual acuity of at least 20/20 (with or without optometric correction) and a monocular visual acuity of at least 20/25 in each eye. Visual acuity was assessed at 3 m under the recommended illumination. None of the participants had a color vision anomaly as assessed by the Farnsworth-Munsell 100-Hue test. The majority of both migraine and control participants were first year undergraduates doing a B.Sc. in Psychology who participated for course credit, a minority were second year B.Sc. undergraduates, postgraduate students and staff from the Department of Applied Psychology at Griffith University.

INSERT TABLE 1 HERE

No participant had taken any acute medication within the 48 hours preceding the test and none was on any daily medication (e.g. migraine prophylaxis, antidepressants or beta-blockers). None were tested while currently having a migraine or headache and none reported experiencing migraine or headache within 48 hours either side of the test session. Ethical approval was obtained from the Human Research Ethics Committee of Griffith University, and informed signed consent was obtained in accordance with the declaration of Helsinki (1991).

Apparatus

The gratings were created using experimental scripts developed in Matlab 7.7 (The MathWorks, Natick, MA) in conjunction with routines from the Psychophysics Toolbox[26,27]. The stimuli were presented on a 21 inch CRT monitor (Hitachi) connected to an Apple

Macintosh computer running MacOS X. The CRT monitor had a spatial and temporal resolution of 1280 x 960 pixels, and 100 Hz, respectively. The CRT monitor was the only source of light in an otherwise dark room.

Visual discomfort/pattern sensitivity and striped patterns

As described in the Introduction, visual discomfort/pattern sensitivity/pattern glare refers to the discomfort and illusions or distortions that can be experienced when viewing repetitive patterns such as stripes[3-6], hereafter termed 'pattern sensitivity' to distinguish it from the visual discomfort questionnaire responses obtained from the Conlon *et al*. questionnaire[7]. Pattern sensitivity to achromatic patterns was assessed by obtaining participants' responses to a series of high-contrast black on white horizontal square-wave gratings presented within a square window (width 7.8°) on the CRT and viewed at 60 cm. The black and white selected had the chromaticity co-ordinates of the CIE standard Illuminant C. The light and dark bars of the gratings had luminances of 36.5 and 2.0 cd m^{-2}, respectively, giving a Michelson contrast of 0.9 (see Table 2).

INSERT TABLE 2 HERE

The 'white' of the achromatic pattern (Illuminant C) was used as a reference neutral for the colored gratings. The +S (purple) and –S (yellow) gratings lay on a tritan line passing through this neutral. For these colors, only the responses of the S-cones varied. The +L(–M) (pink/red), –L(+M) (green) and neutral gratings lay on a line of constant S-cone activity, where only the responses of the L- and M-cones varied. Their chromaticity co-ordinates in the Macleod-Boynton color space[15] are presented in Table 2. The saturation of the colors was selected so as to be approximately equally salient, relative to the neutral[28,29]. Luminance contrast was equal in all five grating displays. The maximum luminance for each grating was constrained by the brightest purple (+S) that could be displayed on the CRT.

The square-wave achromatic gratings were presented with spatial frequencies of 0.5, 3 and 12 cycles per degree (cpd). Each stimulus was presented three times for ten seconds. After each presentation, participants were asked whether they experienced any illusions and, if so, whether they saw (1) motion, (2) color or (3) shape. They were also asked to rate each pattern on a five-point scale, where 1 denoted the pattern was very pleasant, 3 denoted the pattern was neither pleasant nor unpleasant, and 5 denoted the pattern was very unpleasant. Finally, they were asked if the pattern was difficult to view. A general illusion index (GII) was calculated, reflecting overall sensitivity to the experience of distortions and illusions in the patterns[22,30]. First, the frequency with which color, motion and shape were seen was determined for each pattern (minimum zero of three presentations; maximum, three of three). These were then averaged across the patterns and finally summed to give the GII for the achromatic gratings.

The 0.5 cpd achromatic grating was included as a control condition, as it should be the least aversive to view and should generate the fewest distortions or illusions[3]. The colored gratings were presented with spatial frequencies of 3 and 12 cpd only.

Visual Discomfort Questionnaire

The Conlon et al.[7] visual discomfort questionnaire consists of 23 items each with a four-point rating scale to quantify the severity of symptoms, coded zero to three. Scores can therefore vary between zero and sixty-nine. This questionnaire principally assesses discomfort during reading (e.g. "Do you ever get a headache from reading a newspaper or magazine with clear print?" "Do the letters on a page of clear text ever go blurry when you are reading?" "When reading, do the words on a page of clear text ever appear to fade into the background then reappear?" "Do you ever have difficulty reading the words on a page because they begin to flicker or shimmer?" "Does the white background behind the text ever appear to move,

flicker, or shimmer making the letters hard to read?"). Since the discomfort questionnaire predominantly asks about distortions and discomfort while reading, the revised adult dyslexia test was also included to assess discomfort from reading, and reading proficiency, separately[31].

Auxiliary Screening Measures

In addition to visual acuity and visual discomfort, the following measures were also recorded for each participant (i) the Farnsworth-Munsell 100-Hue test, to screen for normal color vision; (ii) contrast sensitivity using the Cambridge Low Contrast gratings (CLCG[32]); (iii) a migraine trigger inventory, which included potential visual triggers; (iv) stereopsis using the Titmus test, to screen for anomalies of binocular function. The results of the Titmus stereopsis test have been presented elsewhere and, therefore, are not presented in detail here[24]. Briefly, there were no group differences on stereo acuity, nor significant correlations between this measure and other experimental measures, due to ceiling effects: each group had excellent stereo acuity.

The Farnsworth-Munsell 100-Hue test consists of 85 colored caps that incorporate a complete hue circle. The caps are presented in four trays, each with two anchored end colors. The remaining colored caps for each tray are given to participants in a random order and must be arranged to form a smooth color sequence between the two reference end colors in each tray. The test was administered under the recommended simulated daylight illumination (Richmond Daylight Illuminator 1339R). Total and partial error scores were calculated for each participant. The partial error scores represent a red-green axis (caps 13-33 and 55-75) and a blue-yellow axis (caps 1-12, 34-54 and 76-85). Errors made for these two axes are used to assess discrimination performance for the L- and M-, and S-cone, pathways respectively. As recommended, cube root total and partial error scores were calculated for the analyses[33-37].

The CLCG measures contrast thresholds for gratings with a spatial frequency of 4 cpd, close to the maximum of the normal human visual system. The gratings were assessed at 6 m. They include 10 plates that display a horizontally oriented square wave grating with Michelson contrasts that range from 13% to 0.14%. The plates are presented to participants in pairs, each presentation consisting of a grating and a blank plate that has the same mean reflectance as its grating pair. Participants must make a two-alternative forced choice when they indicate which of the two plates contains the grating. The test was completed in order of decreasing contrast. Each time an error was made, the sequence was restarted at three plates preceding the error. The plates where errors were made were recorded on three runs through the sequence.

The questionnaire contained a migraine trigger inventory that included visual stimuli. Participants were asked whether each item commonly, occasionally, or never triggered migraine (or headache for the control group). 'Commonly' was scored as two, 'occasionally' as one, and 'never' as zero. A visual trigger index[22,30] was calculated by averaging the scores for each of the four visual items (1: flickering light, 2: striped patterns, 3: alternating light and shade, and 4: other self-cited visual stimuli e.g. lattices, glare, computer use or television).

Procedure

The visual discomfort questionnaire[7] and dyslexia inventory[31] were completed as part of a large class exercise, or sent to potential participants to be completed before the experimental session. In the experimental session, in a dedicated lab, participants were then tested individually. The headache questionnaire and the tests of visual acuity, color vision, contrast sensitivity and stereopsis were assessed at the beginning of the experimental session. Participants were then assessed for pattern sensitivity using the achromatic

gratings. The 0.5 cpd grating was presented first as a control condition, the 3 and 12 cpd gratings were then presented in random order. Each achromatic grating was presented three times for ten seconds each. The four colored gratings were then presented in counterbalanced order. Each of the colored gratings was presented only once for ten seconds each. For each colored grating, the order of presentation of the 3 and 12 cpd gratings was determined randomly.

RESULTS

Most of the statistical analyses were performed using PASW statistics version 18.0 (SPSS Inc., Chicago, IL, USA), apart from the Sign tests, which were calculated by hand. The cube root transformed Farnsworth-Munsell 100-Hue test scores, the contrast sensitivity thresholds, the GII, the composite visual trigger index (VTI), the discomfort scale[7] and dyslexia questionnaire scores[31] were normally distributed for each group (Kolmogorov-Smirnov tests, $p>0.05$), so parametric analyses were conducted. The ratings of the pleasantness/unpleasantness of each grating, and of whether each grating was difficult to view, were derived from limited scales and were not normally distributed. These data were analysed with the non-parametric Sign test.

Farnsworth-Munsell 100-Hue test

Performance on the Farnsworth-Munsell 100-Hue test declines with age, with error scores increasing particularly for the blue-yellow partial error scores. Participants were, therefore, first allocated into age groups binned by decade to compare their performance with published norms[33-35]. Both the migraine and control groups' mean total error scores for the Farnsworth-Munsell 100-Hue test fell within the 95% confidence intervals of a normal population, as has been reported previously[22,36]. The migraine group with visual aura had slightly larger average total and partial error scores than the MO or control groups, as has also been reported previously[22,36]. Cube root total and partial error scores, however, did not

differ significantly between the migraine and control groups (three one-way ANOVAs on each type of error score with group as the between subjects factor, all F's<1, p>0.1, Table 3). Thus, the participants in each group scored within the normal range for color discrimination, with no evidence of significant errors on either the blue-yellow axis or the red-green axis, and the groups did not differ significantly from each other.

INSERT TABLE 3 HERE

Contrast Sensitivity

Both migraine groups had slightly higher CLCG contrast thresholds than the control group, as has been reported previously[4,24]: they needed higher contrasts to be able to correctly identify which of two plates contained the grating, but the migraine groups did not differ from each other (Table 3). The group difference (migraine vs control) was confirmed as statistically significant with a one-way ANOVA with Group as the between subjects factor [$F(1,41)=4.9$, $p<0.05$] and planned comparisons: both migraine groups had significantly higher CLCG contrast thresholds than the control group [VA vs C: $t(26)=2.3$, $p=0.03$; MO vs C: $t(26)=2.4$, $p=0.02$, one-tailed tests]. These data have been presented in more detail elsewhere[22] and are included here principally to assess any association with the measures of visual discomfort later in the results section.

Visual Triggers

Both migraine groups reported that more visual triggers commonly triggered a migraine than the control group reported that visual triggers commonly triggered a headache, as has been reported previously[5,6,22]. The migraine groups also reported a greater number of multiple visual triggers than the control group (Table 3). The commonest visual triggers differed between the migraine and control groups. In order, the VA group reported flicker as the most prevalent trigger (N=9), then computer use or overuse (N=6), stripes (N=5), patterns of light and shade (N=4), television (N=4), the cinema (N=1) and bright fluorescent pink

and green color contrasts (N=1). Similarly, computer use or overuse was endorsed as a trigger by the majority in the MO group (N=9), followed by flicker (N=8), then patterns of light and shade (N=5); stripes (N=4); cinema (N=3); television (N=2) and high contrasts (abrupt transitions from light to dark, N=2; driving at night with oncoming car headlights, N=1). In comparison, the most frequently cited visual headache trigger in the control group was again computer use or overuse (N=7), but the remaining items were endorsed less frequently. Flicker was cited by three, then television, reading, stripes and patterns of light and shade (N=1 for each item).

These group differences were confirmed with a one-way ANOVA on the composite VTI [$F(2,41)=5.3$, $p<0.01$]. Post-hoc Tukey HSD tests revealed that both migraine groups had significantly higher visual trigger indices than the control group [VA vs C: $p=0.023$; MO vs C: $p=0.017$, two-tailed tests] but they did not differ from each other (VA vs MO: $p=0.9$, Table 3).

Visual Discomfort Scale

The Conlon et al.[7] visual discomfort scale scores range from zero to sixty-nine. As expected, both migraine groups had higher discomfort scores (Table 3). A one-way ANOVA, with Group as the between-subjects factor, produced a significant effect of Group ($F(2,41)=4.9$, $p<0.05$). Planned comparisons revealed that both migraine groups had significantly higher discomfort scores than the control group [VA vs C: $t(26)=3.2$, $p=0.003$; MO vs C: $t(26)=2.5$, $p=0.02$], but did not differ from each other [$t(26)=0.6$, $p=0.5$]. On the other hand, the total or partial dyslexia scores[31] did not differ significantly among the groups (two one-way ANOVAs, with group as the between-subjects factor, both Fs<1.4, *NS*). Thus, there were group differences on the visual discomfort scale when reading text (usually a black on white striped pattern), but no group differences on the dyslexia questionnaire scores, which asks about reading and comprehension. The discomfort therefore appears to be related to

the visual characteristics of text as a high contrast striped pattern and not to reading or reading difficulties *per se.*

Visual Discomfort in Achromatic gratings: general trends

1. The number of participants who saw illusions with each spatial frequency (3 cpd > 12 cpd > 0.5 cpd)

It was expected[3] that fewest illusions would be reported with the lowest spatial frequency achromatic grating (0.5 cpd) and that there would be little difference between the three groups for this grating. The number of people seeing illusions should increase for the mid and high spatial frequency gratings and group differences may emerge. The number of people who saw an illusion of color, motion or shape in at least one of the three presentations of each achromatic grating was calculated for each spatial frequency and each participant (Table 4).

As expected, only a small number of people reported seeing an illusion in at least one presentation of the low frequency (0.5 cpd) achromatic grating, however, the majority of participants in each group saw at least one illusion in the mid-spatial frequency grating (3 cpd). A comparable number of the migraine participants saw at least one illusion in the high spatial frequency pattern (12 cpd). In contrast, in the control group, twice as many people saw illusions with the 3 cpd grating than with the 12 cpd grating (Table 4).

INSERT TABLE 4 HERE

2. The most common illusion seen with each spatial frequency (shape > motion > color)

It was expected[3,4] that illusions of shape would be most frequently reported, followed by motion and then color. Overall, this expectation was borne out, although not consistently, as there were sometimes slightly more reports of illusory motion than of illusory shapes for the migraine groups (Table 4).

When color was reported, it was seen either as a wash of color over the display or as a colored shape in the background. Reds were seen the most frequently, yellow was reported the least frequently, and green and blue were in-between. Only a few people actually reported illusions of color, however, and the greatest number was with the 3 cpd grating (Table 4).

Often reported illusory shapes were geometric such as a lattice, diamonds or circles seen behind the stripes, but less geometric shapes were also reported including flames, petals, or teardrops. Several reported the stripes disappeared entirely to become a solid block of grey or black, others reported a patchy disappearance of parts of the display.

In the migraine groups, the illusory motion was described as a pulsating motion as if the stripes were breathing, or the stripes vibrated, flickered, oscillated or moved up and down, or waves rippled through them like waves in water. Three reported dots, rain or snow running over the pattern of stripes. Sometimes the stripes themselves were reported as moving, bending or pulsating, yet sometimes the motion was seen in an illusory shape or as an illusory moving color. In the control group, the illusory motion was most commonly reported as jitter or vibration. Other experiences included sore eyes, pain in the eye, pain in the head, blinking, being aware of after-images, blurring of the image and finding it difficult to focus.

3. Changes in the experience of each achromatic grating over time

The achromatic gratings were presented three times for ten seconds each to determine whether the illusions, and the ratings of the patterns, changed with repetitive viewing. Any changes in the occurrence of each type of illusion from presentation one to presentation three were assessed using Sign tests. As this test has low power, the data for the migraine groups with and without aura were combined. Correction for multiple testing was not performed as the separate parameters (illusion types, ratings of discomfort and difficulty of viewing) were considered as separate dependent variables. Nevertheless, these analyses should be considered as exploratory.

For the low spatial frequency grating (0.5 cpd), there were no significant changes from the first to third presentation in the number of people who reported illusions of either color, motion or shape, or who reported the grating difficult to view, in either the combined migraine or the control groups ($p>0.05$). The ratings did, however, become slightly but significantly less pleasant from presentation one to presentation three for the combined migraine group (total changes $N=5$, positive changes $N=5$, negative changes $N=0$, $p=0.03$).

For the mid spatial frequency pattern (3 cpd), there were no significant changes from the first to third presentation in any of the parameters measured for either the combined migraine or the control groups ($p>0.05$).

For the highest spatial frequency pattern (12 cpd), there was a significant increase in the number of people with migraine reporting illusions of shape from the first to the third presentation (total changes $N=12$, positive changes $N=10$, negative changes $N=2$, $p=0.02$). There were no significant changes in the number of people with migraine who reported illusions of color or motion or who reported the grating difficult to view, nor did the

pleasantness of the ratings change. There were no significant changes in any of the measures recorded from the control group.

4. The GII

The GII is a composite measure from the three presentations of each of the three achromatic gratings (0.5, 3 and 12 cpd) and represents each participant's overall sensitivity to the experience of distortions and illusions in the striped patterns. Both migraine groups had larger GII scores than the control group, as has been reported previously[22,30] (Table 3). A one-way ANOVA revealed a significant effect of group ($F(2,41)=5.0$, $p=0.012$). Planned pairwise comparisons showed that the VA group experienced more illusions than either the control or MO groups, [VA vs C: $t(26)=3.4$, $p=0.002$ (one-tailed test); VA vs MO: $t(26)=2.3$, $p=0.03$ (two-tailed test)]. The MO group also had higher GII scores than the control group, as expected, but the difference was not statistically significant [$t(26)=1.3$, *NS,* one-tailed test]. As can be seen in Table 4, the differences between the migraine and control groups largely arose due to differences in the number of illusions seen in the 3 and 12 cpd gratings.

Visual Discomfort in Chromatic gratings: general trends

1. The number of participants who saw illusions with each colored grating and each spatial frequency

With the *achromatic* gratings, the majority of participants in each group saw at least one illusion in the mid-spatial frequency grating (3 cpd), and a comparable number of the migraine participants saw at least one illusion in the high spatial frequency pattern (12 cpd). In the control group, however, twice as many people saw illusions with the 3 cpd grating than with the 12 cpd achromatic grating (Table 4). These responses to the achromatic gratings were used as a baseline to compare the experience of each colored grating in each group. The changes in the experiences of each person's view of each colored grating, relative to the achromatic ones, were assessed with Sign Tests. Correction for multiple testing was

not performed for these analyses for the same reasons given above for the achromatic gratings. Overall group differences on a tally of illusions (a chromatic GII, see below) were assessed with four one-way ANOVAs, one for each color.

It might be expected that the color of each display would influence the subjective reports of any illusory colors seen in that display. When illusions of color were reported with the red, green and yellow colored gratings, however, there was no preponderance of one color over another. Reds were reported as often as blues, yellows, or greens. On the other hand, with the purple gratings, only blues and yellows were reported. Overall, however, there were no significant changes in the reporting of colored illusions with each colored grating, compared to the achromatic ones, probably attributable to the small number of people who saw illusions of color in any of the gratings anyway (see below, and Tables 3 and 4).

+S gratings (purple)

Three cpd grating. There was a significant *decrease* in the number of people in the combined migraine group who reported illusions of motion and of shape (but not of color) when viewing the +S 3 cpd grating, compared to the achromatic, 3 cpd, grating (for both motion and shape: total changes $N=9$, positive changes $N=1$, negative changes $N=8$, $p=0.02$). Conversely, there were no significant differences in the number of people in the control group who saw any of the illusion types. The ratings of pleasantness also did not differ between the +S and achromatic 3 cpd gratings in either group, nor did the number of people who found the patterns difficult to view differ significantly.

INSERT TABLE 5 HERE

Twelve cpd grating. There was a significant *decrease* in the number of people in the combined migraine group who reported illusions of shape (but not of color or motion) when viewing the +S 12 cpd grating, compared to the achromatic, 12 cpd, grating (total changes for shape: N=17, positive changes N=15, negative changes N=2, p=0.001). The ratings of the +S grating also *increased* in pleasantness significantly in the migraine group (total changes N=10, positive changes N=0, negative changes N=10, p=0.001) and the number who reported the +S grating difficult to view *fell* significantly (total changes N=6, positive changes N=0, negative changes N=6, p=0.02). There were no significant differences for any of the measures for the control group.

–S gratings (yellow)

Three cpd grating. There was a significant *decrease* in the number of people in the combined migraine group who reported illusions of motion when viewing the –S 3 cpd grating, compared to the achromatic 3 cpd gratings (total changes N=12, positive changes N=2, negative changes N=10, p=0.02). There were no significant changes for the other measured parameters in the migraine group, and none at all in the control group.

Twelve cpd grating. There was a significant *decrease* in the number of people in the combined migraine group who reported illusions of shape when viewing the –S 12 cpd grating, compared to the achromatic, 12 cpd grating (total changes N=11, positive changes N=1, negative changes N=10, p=0.006). There were no significant changes for the other measured parameters in the migraine group, and none at all in the control group.

–L(+M) gratings (green)

Three cpd grating. There were no significant changes for any of the parameters measured when viewing the –L(+M) or the achromatic 3 cpd gratings for either group.

Twelve cpd grating. The number of people with migraine reporting illusions of shape *decreased* significantly when viewing the –L(+M) 12 cpd gratings, compared to the achromatic 12 cpd ones (total changes N=12, positive changes N=1, negative changes N=11, p=0.003). There were no significant changes for the other measured parameters in the migraine group, and none at all in the control group.

+L(–M) gratings (red)

Three cpd grating. The number of people with migraine reporting illusions of color and motion *decreased* significantly when they viewed the +L(–M) 3 cpd grating, compared to the achromatic one (color: total changes N=6, positive changes N=0, negative changes N=6, p=0.016; motion: total changes N=13, positive changes N=3, negative changes N=10, p=0.046). There were no significant changes for the other measured parameters in the migraine group, and none at all in the control group.

Twelve cpd grating. The number of people with migraine who reported illusions of shape (but not of color or motion) *decreased* significantly when viewing the +L(–M) grating, compared to the achromatic 12 cpd grating (total changes N=12, positive changes N=0, negative changes N=12, p=0.0002). The ratings of pleasantness/unpleasantness also *increased* in pleasantness significantly, (total changes N=12, positive changes N=2, negative changes N=10, p=0.02). The judgments of whether the pattern was difficult to view also *decreased* (total changes N=5, positive changes N=0, negative changes N=5, p=0.031). There were no changes in any of the measured parameters for the control group.

Group differences with the chromatic gratings

Four GIIs were calculated from the responses to each chromatic grating in the same way as for the achromatic gratings (Table 6). There were no significant group differences for any of the colored gratings, which is consistent with the *decreases* in the number of illusions seen by the migraine groups described above when color was employed [four one-way ANOVAs with group as the between subjects factor, largest $F(2,41)=1.4$, $p>0.24$]. This is in contrast to the achromatic GII, where both migraine groups saw a greater number of illusions than the control group (Table 3).

INSERT TABLE 6 HERE

Correlations between the various measures

There were a few significant correlations between the various measures. The achromatic GII correlated significantly with the number of years migraine had been experienced ($r=0.44$, $N=28$, $p=0.02$): those with the longest duration migraine saw the greatest number of illusions. The achromatic GII also correlated significantly with reports of any visual migraine triggers ($r=0.29$, $N=28$, $p=0.03$): those who saw the most illusions also reported the most visual triggers. Finally, the achromatic GII correlated significantly with each of the four colored GIIs (smallest $r=0.36$, largest $r=0.62$, $N=42$, $p<0.05$). Similarly, the colored GIIs were significantly inter-correlated (smallest $r=0.47$, largest $r=0.63$, $N=42$, $p<0.005$). The colored GIIs, however, did not correlate significantly with any of the other measures.

The responses to the Conlon *et al.*[7] visual discomfort questionnaire correlated significantly with reports of visual migraine triggers ($r=0.50$, $N=28$, $p=0.001$): those with the greatest discomfort also reported the largest number of visual migraine triggers. Responses to this questionnaire also correlated significantly with the total and partial revised dyslexia questionnaire scores[31]: those with the greatest discomfort also had the highest scores on the

dyslexia questionnaire (total dyslexia score: r=0.46, p=0.002; partial dyslexia score: r=0.42, p=0.006, N=28 for both). There were no significant associations between the discomfort scale responses and any of the GIIs. Finally, the measure of contrast sensitivity from the CLCG correlated significantly with reports of any visual migraine triggers r=–0.45, N=28 p<0.05. The negative correlation indicates that those with visual triggers performed more poorly on the contrast sensitivity task.

There were also some expected significant associations, such as: the correlations between age and the number of years migraine had been experienced (r=0.81, N=28, p<0.001); the frequency of migraine and the days elapsed since the last migraine attack (r=–0.34, N=28, p=0.03); and between different visual triggers (stripes, flicker, patterns of light and shade, other visual triggers such as computer overuse, smallest r=0.31, p=0.048, largest r=0.48, p=0.001, N=28 for both).

There were no other significant correlations between the various measures tested: age, years migraine experienced, frequency of migraine, last migraine attack, visual trigger index[22,30], visual discomfort scale[7], dyslexia scores[31], achromatic GII, chromatic GIIs, contrast sensitivity thresholds, or cube root Farnsworth-Munsell scores.

DISCUSSION

This study aimed to identify possible pathways involved in the beneficial effects that color can have in alleviating visual discomfort that can be experienced when viewing striped patterns. In particular, this study was designed to assess any pre-cortical contribution to the experience of, or reduction of, visual discomfort with color by using four colors that lay along the two cardinal color directions. This is the first study to look at visual discomfort and its alleviation using such colors that independently stimulate the pre-cortical cone-opponent color pathways.

As expected, the migraine groups experienced a greater number of illusions in the *achromatic*, black and white, patterns than the control group[3,4,8,38,39]. Also as expected, illusions of shape were mostly reported across all conditions more frequently than illusions of motion or color, although illusions of motion were sometimes more common for the migraine groups. Finally, there seemed to be few cumulative effects of the three repetitions of the achromatic striped patterns. Repeated presentations were included in the study following a report[40] that pain elicited by flickering light (five flashes per second), in both headache and control groups, could be reduced with prolonged repetitive exposure and tolerance to such stimuli also increased slightly. Visual disturbance ratings of the headache group in that study also fell slightly, but not significantly, compared to the control group, after prolonged repetitive viewing. That study recruited non-specific headache and control groups, however, a similar result has been reported for unpleasant, intense noise stressors in migraine, but not in tension type headache[41]. Here, however, there was no evidence that repetitive exposure to the *achromatic* striped patterns reduced either the number of illusions seen or an aversive response. Indeed, the few changes that did occur over time were in the opposite direction. It should be noted, however, that the earlier studies used longer stimulus durations than those used here. Short repetitive presentations were employed here so as not to induce pain, headache or migraine.

One explanation for the illusions that are seen is that the high contrast, achromatic gratings, create such an excessive neuronal response in cells tuned to the properties of the patterns that activity can spread and neighbouring cells in a local network can be inadvertently recruited to fire as well. If the recruited cells are selective for color, depth, or motion, etc, then these percepts will also be seen[3,11,38]. The physical discomfort and feelings of unpleasantness could be the by-product of this spreading activation. Increased illusions and discomfort in migraine may indicate that the inappropriate spread of activity happens more readily, perhaps due to a general neuronal hyperexcitability[3], perhaps due to impoverished

inhibitory pathways failing to modulate the massive excitation generated by the patterns, or perhaps due to hypoexcitability and competition between excitation and inhibition. These alternative explanations have been described in more detail elsewhere[38]. Here, the emphasis is on the changes in visual discomfort with color.

It was found that all four colors reduced to some extent the number of illusions and distortions seen in the high contrast gratings, particularly in the migraine groups for the 12 cpd grating. Furthermore, the +S (purple) and +L(-M) (red/pink) backgrounds also increased the ratings of pleasantness and decreased judgments of whether the gratings were difficult to view, compared to the achromatic gratings, in migraine. All of the gratings had the same high luminance contrast, so the changes in the experience of illusions and in the ratings were the result of the colored backgrounds for the migraine groups. The reduction in the number of illusions and discomfort with each color implies that the colors decreased the spread of activation and reduced the recruitment of additional cells. This further suggests that the neuronal response to the colored gratings was less than the response to the achromatic ones. Thus, the use of colored backgrounds reduced an excessive neuronal response to high contrast gratings.

Perhaps surprisingly, the Farnsworth Munsell 100-hue test total and partial error scores did not correlate significantly with any of the chromatic GIIs. Furthermore, these scores revealed no overall color sensitivity abnormality in the migraine or control groups. There was no evidence of significant errors on either the blue-yellow axis or the red-green axis in any of the groups, and the groups did not differ significantly from each other. This was unexpected given earlier work that has shown anomalous activity in specific pre-cortical pathways for other tasks in migraine, specifically in the tritan cone-opponent pathway[22,36]. It is possible that this result arose from the particular sample recruited: most were relatively young undergraduates so there was less variation in scores, and the sample size was smaller than in the previous work so power was consequently lower.

The similarity of results for each color is consistent with previous reports that a range of colors are selected as optimum by different participants to reduce discomfort. This may be due to a re-balancing or changing of striate and extrastriate cortical activation as proposed by Huang *et al.*[21], yet it may also reflect changes in neural activity in both of the cone-opponent pathways. All color perception relies on the cone-opponent pathways that connect the retina to the cortex, which were isolated here with the use of cardinal colors. These two pathways are combined in the cortex, but a pre-cortical anomaly in one or other pathway will carry over into higher level color processing. It would be useful to analyse the optimum colors reported in previous studies[3,11-14] to determine what activity they produce in the cone-opponent pathways to see whether, for different observers, an individual's optimum color is selective for one or other. It is also possible that color saturation as well as color is important to alleviate discomfort for different individuals along these two pathways and re-analysis of the colors selected in previous studies may provide evidence for this. Here, we selected cardinal colors that were equated for salience/saturation relative to neutral[28,29] (Table 2). Color saturation could be examined in future research. Work in preparation has looked at the specificity of color choice, when people are tested with a wider range of colors, to confirm the general beneficial effects of color and a bias for purples and pinks as colored backgrounds. Further work on the +S and +L(-M) colors reduction of aversion and increase in pleasantness ratings would be warranted.

The combination of the cone-opponent channels in the cortex results in a modified representation of colors in two additional channels defined by color-opponency rather than cone-opponency. The former relies on perception and the latter relies on the spectral power or wavelength distribution present in the displays. The color-opponent channels are defined by: 1. unique red—neither orangey nor purplish—vs unique green—neither yellowish nor bluish; 2. unique blue–neither greenish nor purplish—vs unique yellow—neither reddish nor greenish[42,43]. These channels were initially proposed based on the observations that a

reddish-green is not imaginable, nor is a yellowish-blue, yet other combinations are (e.g reddish-yellow, bluish-green, reddish-blue). A further extension would be to assess the beneficial effects of these unique hues to alleviate discomfort.

A surprising result was the lack of significant correlations between many of the measures. While there were group differences consistent with previous reports (contrast sensitivity assessed with the CLCG[4,24]; visual triggers[5,6,22]; visual discomfort scale[7]) there were few significant correlations between the different measures. There were some expected correlations, for example, the achromatic GII, the Visual discomfort scale[7], and contrast sensitivity all correlated significantly with reports of visual triggers. The chromatic GIIs, only correlated significantly with themselves. It is possible that the significant association between the achromatic GII and visual triggers, and the lack of a significant association between the chromatic GIIs and visual triggers, may have a parallel in the reduction of visually triggered migraine with the use of color.

The numbers of people with migraine reporting illusions with the 3 cpd and 12 cpd achromatic gratings were comparable. Evans and Stevenson[39], however, have recommended that indices of pattern glare or pattern sensitivity can be calculated either by using the number of distortions reported with a 3 cpd pattern, or by calculating the difference between the number of distortions seen with the 3 and 12 cpd gratings, the "3-12 cpd difference". The present results, however, indicate that the 12 cpd patterns were just as aversive and generated as many illusions as the 3 cpd pattern and, indeed, the beneficial effects of color were more pronounced for the 12 cpd pattern in migraine. Here, the "3-12 cpd difference" was only meaningful for the control group. This result stands in contrast to other reports using the "3-12 cpd difference" as a measure of visual discomfort in migraine and control groups[5,39].

These discrepancies suggest that the commercially available clinical Pattern Glare test[39] needs a further review of its applicability. It is possible that it is more useful with older migraine patients, rather than with the mostly younger patients tested here, since the achromatic GII (a measure of pattern glare/pattern sensitivity) did correlate significantly with the number of years migraine had been experienced. An alternative suggestion would be to use the '3+12' cpd illusion sum, rather than their difference, as a measure of visual discomfort. These alternatives could be explored in future research with participants covering a larger age range. Future research should also replicate the studies that suggest repetitive lengthy exposure to visual (or other) migraine triggers can desensitise patients to those triggers[9,40,41]. Color could be incorporated in a grating desensitisation procedure to reduce visual discomfort during presentation of the trigger stimuli. Colored gratings should be better tolerated and less aversive than achromatic ones and yet any sensitivity changes may generalise.

In the shorter term, clinicians may find it useful to include measures such as the GII or the visual discomfort scale when assessing patients with headache and migraine, to gain a more thorough representation of the prevalence of visual discomfort in their clinics. It would also be useful if clinicians asked their migraine patients specifically whether visual stimuli trigger their migraine, in addition to factors such as stress, diet, sleep and hunger, and ask about interictal visual symptoms. Positive responses to questions on triggers and interictal symptoms, together with high GII or visual discomfort scores, would indicate the patient may benefit from the use of color. Patients could be encouraged to explore color, whether the use of a tinted computer background at work, tinted lenses, or colored overlays, as a possible palliative for their visual discomfort. Finally, further work is needed to compare differences in efficacy between colored computer backgrounds, tinted overlays and tinted glasses, to see whether the extent of the field of view that is colored is important to the alleviation of discomfort with color.

CONCLUSION

This study has confirmed that features of the visual environment, such as glare, flicker and repetitive geometric patterns, are reported to provoke migraine and other headaches[2,5,6] (Table 3). It has also confirmed the association between those who report that visual stimuli can act as migraine or headache triggers and the experience of visual discomfort, as assessed by both the achromatic GII and the Conlon *et al*.[7] visual discomfort scale. The remarkable result was that all four colored gratings, which had the same luminance contrast as the achromatic gratings, reduced visual discomfort and two (purple and pink) reduced aversion compared to the achromatic gratings. Further work on the use of color to reduce discomfort, and the relationship between color and the possible reduction of visually triggered migraine, is recommended.

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Table 1. Participant details in the form of group means, ± 1 standard deviation, and ranges (in parentheses) for each measure. F = female, M = male, VA = migraine with aura, MO = migraine without aura, C = control group.

Group	Age (years)	Migraine duration (years experienced)	Last migraine attack (days)	Migraine frequency (per year)
VA	24.6 ± 8.7	12.1 ± 8.3	33 ± 49	12 ± 7
12 F, 2 M	(17–43)	(2–30)	(3–180)	(4–26)
MO	24.6 ± 5.9	10.4 ± 4.4	49 ± 48	8 ± 9
13 F, 1 M	(17–38)	(4–17)	(3–170)	(2–40)
C	Age		Last headacbe	Headache frequency
10 F, 4 M	23.1 ± 8.5		37 ± 33	7 ±6
	(17–44)		(2–100)	(1–20)

Table 2: Stimulus characteristics of the striped patterns used to gauge visual discomfort. Y: luminance of the white (CIE Illuminant C) or colored bars in cdm^{-2} (the luminance of the black bars was 2.0 cdm^{-2} for each grating); Y contrast: Michelson luminance contrast of each grating; MB (r,b): MacLeod-Boynton (1979) chromaticity co-ordinates of the white, red, green, purple and yellow bars (13); L-, M-, S-contrast: chromatic contrasts of the bars of the gratings for the L-, M-, and S-cones. The chromatic contrasts are expressed as (r,b) chromaticity co-ordinate differences in a logarithmic transformation of the MacLeod-Boynton diagram (i.e. L contrast: log(r)–log(r, Illuminant C); M contrast: log(1-r)–log(1-r, Illuminant C); S contrast: log (b)-log(b, Illuminant C). In the transformed diagram equal distances between pairs of points correspond to equal perceived hue differences, at least for colors near neutral/Illuminant C (after 28,29).

Grating	**Y**	**Y contrast**	**MB (r,b)**	**L-contrast**	**M-contrast**	**S-contrast**
Achromatic (white/black)	36.3	0.9	0.656, 0.018	0	0	0
+L–M (red/black)	36.3	0.9	0.709, 0.018	0.033	–0.071	0
–L+M (green/black)	36.5	0.9	0.605, 0.018	–0.036	0.061	0
+S (purple/black)	36.2	0.9	0.656, 0.042	0	0	0.369
–S (yellow/black)	36.2	0.9	0.656, 0.008	0	0	–0.369

Table 3: Results for the Farnsworth-Munsell test, contrast thresholds (CLCG), and susceptibility to visual triggers. FM = average cube root transformed Farnsworth Munsell error scores ± one standard deviation, R-G, B-Y = partial error scores for the red-green and blue-yellow components, respectively. CLCG = average contrast sensitivity thresholds ± one standard deviation, measured as Michelson contrasts. Subsequent columns: the number of participants (N) who cited that at least one visual stimuli (flicker, striped patterns, alternating light and shade, other self-cited visual stimuli) commonly, or occasionally, could trigger migraine or headache. The number of people citing multiple visual triggers (minimum 2, maximum 4) are listed in the subsequent columns. VTI = visual trigger index, an average score for each participant. GII = general illusion index. ***** *denotes a significant group difference (MO, or VA, vs Control) at P<0.05,* ****** *P<0.005.*

	FM error scores			**CLCG**	**Common**	**Occasional**	**Multiple Triggers**			**VTI**	**GII**	**Visual discomfort scale[7]**
	Total	**R-G**	**B-Y**		***N***	***N***	**4**	**3**	**2**			
VA	3.9±1.0	3.0±0.7	3.1±0.9	0.29±0.16*	4	9	2	1	6	1.2±0.6*	3.0±1.1**	25.4±13.6**
MO	3.4±0.9	2.6±0.5	2.6±0.9	0.28±0.13*	5	8	1	4	4	1.3±0.6**	1.9±1.4	22.1±13.6*
C	3.1±1.2	2.4±1.1	2.6±0.9	0.19±0.08	0	10	0	0	2	0.7±0.5	1.4±1.5	11.6±8.2

Table 4: The number of people who reported seeing illusions overall, and the number seeing each type of illusion, in at least one of the three presentations of each of the achromatic gratings. The gratings were rated on a five-point scale where 1=pleasant, 3=neither pleasant nor unpleasant, 5=unpleasant. Whether the gratings were judged to be difficult to view was coded as yes/no and the number of yes responses was tabulated.

Grating	**Number of Illusions**		**Type of Illusion**			**Rating**		**Difficult**
	0	**≥1**	**color**	**motion**	**shape**	**mean**	**range**	**to view**
A: Achromatic (white/black) 0.5 cpd								
VA	10	4	0	3	1	2.8	1–4	2
MO	11	3	0	2	1	3.0	2–4	1
C	12	2	0	1	2	2.8	1–4	1
B: Achromatic (white/black) 3.0 cpd								
VA	3	11	5	9	8	3.0	1–4	5
MO	4	10	1	4	7	2.9	2–5	2
C	4	10	3	5	7	3.0	2–4	4
C: Achromatic (white/black) 12.0 cpd								
VA	1	13	3	7	11	3.4	2–5	5
MO	4	10	2	6	8	3.1	2–4	3
C	9	5	0	3	4	3.1	2–5	3

Table 5: The number of people who reported seeing illusions overall, and the number seeing each type of illusion, in each of the colored gratings. The gratings were rated on a five-point scale where 1=pleasant, 3=neither pleasant nor unpleasant, 5=unpleasant. Whether gratings were judged to be difficult to view was coded as yes/no and the number of yes responses was tabulated. A: 3 cpd grating; B: 12 cpd grating.

Grating	**Number of Illusions**		**Type of Illusion**			**Rating**		**Difficult**
	0	**≥1**	**color**	**motion**	**shape**	**mean**	**range**	**to view**
A: +L(−M) (red/black) 3.0 cpd								
VA	3	11	0	3	10	2.9	1–4	5
MO	6	8	0	3	5	3.1	2–4	2
C	7	7	3	2	6	2.9	2–3	0
−L(+M) (green/black) 3.0 cpd								
VA	5	9	1	3	7	2.9	1–4	4
MO	7	7	1	4	3	3.1	2–4	2
C	7	7	2	2	6	2.9	2–4	0
+S (purple/black) 3.0 cpd								
VA	7	7	1	4	6	2.8	1–4	4
MO	8	6	1	2	3	3.0	1–5	1
C	7	7	3	2	6	2.7	2–4	0
−S (yellow/black) 3.0 cpd								
VA	4	10	0	1	9	3.0	1–4	4
MO	5	9	4	4	6	3.1	2–4	3
C	8	6	2	3	5	2.7	1–3	1
B: +L(−M) (red/black) 12.0 cpd								
VA	6	8	1	4	5	2.9	1–5	3
MO	7	7	0	5	3	2.7	1–4	0
C	7	7	1	3	4	2.9	2–4	1
−L(+M) (green/black) 12.0 cpd								
VA	4	10	1	4	8	3.4	1–5	5
MO	7	7	0	7	2	2.9	2–4	0
C	9	5	2	3	4	3.1	2–5	2
+S (purple/black) 12.0 cpd								
VA	5	9	2	6	5	2.8	1–4	2
MO	10	4	0	4	2	2.8	1–4	0
C	8	6	1	4	5	3.0	1–4	2
−S (yellow/black) 12.0 cpd								
VA	4	10	2	5	7	3.1	1–5	3
MO	5	9	2	4	4	3.0	2–4	1
C	6	8	1	3	6	2.8	2–3	1

Table 6: GIIs for the chromatic gratings (average ± one standard deviation). In contrast to the achromatic GII (Table 3), there were no significant group differences for any of the chromatic GIIs.

Group	**Purple**	**Yellow**	**Red**	**Green**
VA	0.86±0.66	0.86±0.60	0.82±0.57	0.86±0.50
MO	0.43±0.43	0.86±0.53	0.57±0.51	0.61±0.56
C	0.75±0.89	0.71±0.67	0.68±0.72	0.68±0.75