Altered colour induction in migraine: computational simulation and psychophysical results

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Resum– La migranya és un transtorn de mal de cap comú associat a diferències en la percepció visual. Descobriments recents suggereixen que els migranyosos poden tenir un dèficit en el mecanisme neuronal d'inhibició que juga un paper important en la percepció visual. L'inducció del color és la influència del color circumdant (inductor) al color percebut d'una regió central. Hi ha dos tipus d'inducció: assimilació del color i contrast del color, i s'han estudiat extensament en subjectes sense migranya [1–4]. Aquest treball amplia els resultats psicofísics de [4] afegint nous experiments amb migranyosos (amb i sense aura). A causa del dèficit inhibitori, esperem que els subjectes amb migranya mostrin la menor assimilació. Els nostres resultats mostren l'efecte contrari. Per a voltants ratllats, l'assimilació més forta es troba als subjectes de migranya sense aura. En voltants uniformes, s'observa el major contrast en ambdós grups de migranyosos. En totes les condicions, els subjectes de control presenten una menor inducció.

Paraules clau– Inducció de color; Psicofísica; Migranya; Model computacional; Funció de sensibilitat al contrast

Abstract– Migraine is a usual headache disorder associated to differences in visual perception. Recent findings suggest that migraineurs could have a deficit in the inhibitory mechanism which plays an important role in visual perception. Colour induction is the influence of the surrounding colour (inducer) on the perceived colour of a central region. There are two types of induction: colour assimilation and colour contrast, and it has been widely studied in non-migraine subjects [1–4]. This work extends the psychophysical results of [4] by adding new experiments with migraine subjects. Because of the deficit in inhibition, we expect that migraine subjects show the weakest assimilation. Our results show the opposite effect. For striped surround, the strongest assimilation is found in migraine without aura subjects. In uniform surround, the highest contrast is observed in both migraine groups. In all conditions control subjects show the weakest induction.

Keywords– Colour induction; Psychophysics; Migraine; Computational model; Contrast sensitivity function

1 INTRODUCTION

MIGRAINE, the most frequent neurologic disorder worldwide, affects approximately 12% of adults by causing recurrent headaches from moderate to severe pain. The most important factor, among others, to trigger migraines is visual stimuli, which induces intense pain and photophobia during the attacks. Visual symptoms are common in migraine either in the form of aura (manifested as the perception of a strange light in the visual field),

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photophobia, or less specific symptoms such as blur. For this reason, visual perception has been extensively used as a method to indirectly explore brain function in migraine [5–9]. Recent findings suggest that migraineurs show an imbalance between the activity of excitatory and inhibitory cells of the visual system. These excitatory and inhibitory mechanisms are responsible for the encoding of visual information in the visual cortex, which is the neuronal basis of colour perception.

It is known from already published psychophysical studies that the perceived colour of a region is influenced by the colour and the spatial configuration of its surround (its inducer). This effect is called colour induction. There are two types of colour induction: colour assimilation and colour contrast. The former occurs when the central colour shifts toward the colour of the inducer (see top panels of Fig. 1) and the latter when the central colour shifts away from the colour of the inducer [3] (see bottom panels of Fig. 1). Some studies [1, 2, 4] have shown that colour contrast occurs when the surround is a uniform colour and colour assimilation when the surround is striped.

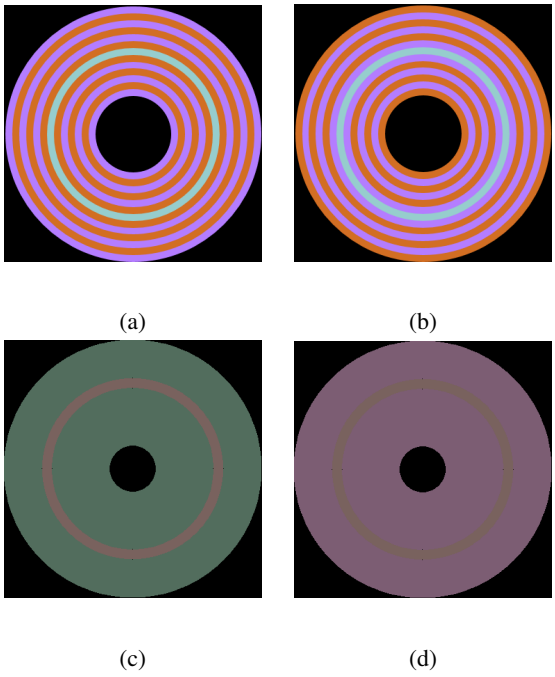


Fig. 1: Centre ring which has the same colour in pairs of stimuli a-b and c-d shows that striped stimuli causes colour assimilation (a and b) and uniform stimuli causes colour contrast (c and d).

Colour visual information is processed by the visual system along several stages. The light arriving at the retina is transformed into electric impulses that are sent to the lateral geniculate nucleus (LGN) through the optic nerve [10]. These nerve impulses arriving at the LGN are separated into three different pathways: parvo-, konio- and magnocellular pathways. Parvocellular pathway encodes the L- and M-cones activity ratio (red-green information), and koniocellular pathway encodes the ratio between S-cones and L+M cones activity (purple-lime information). These two pathways encodes the chromatic information of the visual stimuli, while magnocellular encodes luminance information. Each pathway initially projects to a different layer (4Cβ, 2/3 and 4Cα, respectively) in the primary visual cortex (V1) and they converge into layer 2/3 of V1 [11–14]. In this area, lateral interactions between neurons are responsible for generating perceptual colour induction effects [15, 16]. Visual cortex cells encode colour difference between two visual areas, i.e. the highest the colour difference, the highest the cell activity. Excitatory neural mechanisms increase cell activity, which implies that the perceived difference of colour between two areas is increased, i.e. colour contrast. Similarly, inhibitory neural mechanisms reduce cell activity, which reduces the colour difference between two areas, i.e. colour assimilation.

As suggested by [17, 18], the output of V1 activity of migraineurs show a deficient inhibitory mechanism. Our hypothesis is that migraineurs would show a different perception of colours in comparison to control subjects [17], in particular migraineurs might show a weaker assimilation and stronger contrast than control people.

Several works have studied the differences between migraine and non-migraine subjects in colour perception and discrimination [17, 19–21]. They show that migraine subjects have an impairment in the colour vision of the S-cones, although no differences to control subjects were found in the L- and M-cones. In contrast, up to our knowledge, no colour induction experiments have been conducted to study migraineurs colour perception.

Some computational architectures [4, 22] have been defined to model colour processing in the primary visual cortex, being CIWaM the most simple and efficient one. This architecture models excitatory and inhibitory mechanisms of primary visual cortex to reproduce colour perception.

The aim of this study is to observe whether migraine people have a different colour induction to control subjects. In addition, we intend to reproduce the experimental results using the CIWaM computational model to suggest about the origin of the expected perceptual differences between these populations.

2 GOALS

The goals defined in this project were the following ones:

- Obtain psychophysical results of colour induction for the designed stimuli in three different groups of people (migraine without aura, migraine with aura and non-migraine people).
- Fit several CIWaM parameters using the psychophysical results of the different groups (migraine with and without aura and control).

To achieve these goals the next tasks have been performed:

– Calibrate a CRT monitor using the ColorCal colorimeter.

– Generate experimental stimuli using MATLAB CRS toolbox to present them on the calibrated monitor through the ViSaGe MKII Stimulus Generator hardware.

– Compare the predictions of the model and the psychophysical results.

3 PSYCHOPHYSICAL EXPERIMENTATION

3.1 Experimental setup

The psychophysical experiments were conducted in a controlled environment. The stimuli were viewed binocularly in the dark room from a distance of 140 cm and subtended 16.3×12.2 visual degrees. The stimuli were displayed in a 21" SONY GDM-F500R CRT monitor (1024 × 764 px). Those images were processed through the Cambridge Research Systems ViSaGe MKII Stimulus Generator [23]. This hardware was managed using the Toolbox for MATLAB from the Cambridge Research Systems [24]. The subject's responses were acquired using a Logitec© gamepad.

The monitor was calibrated with a ColorCAL colorimeter that calculates the gamma correction of the three colour signals using the ViSaGe software.

3.2 Stimuli

The code to generate the stimuli was implemented in MATLAB. We chose the same stimuli as [4], which were inspired by [1, 2]. We chose these stimuli because the authors show that striped and uniform surrounds generate different induction effects (colour assimilation and colour contrast, respectively). Striped stimuli are defined by a reference ring and a set of concentric rings with alternating colours, being the first inducer the ring next to the reference ring (Fig. 2). In uniform surrounds, both the first and second inducers have the same colour.

Otazu et al. [4] used three different spatial frequencies. To reduce the experiment duration, we selected the configurations with the two highest spatial frequencies (thinnest ring sizes) because striped surrounds at high frequencies induce more assimilation than at low frequencies [4, 25, 26]. Eight colour conditions (four striped and four uniform) and two spatial frequencies were defined (see representative stimuli in appendix Fig. 9).

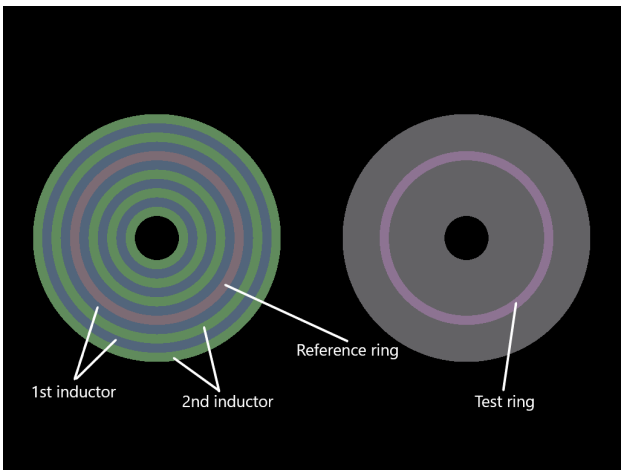


Fig. 2: Design of the stimuli presented on the monitor. Subjects modified the colour of the test ring to perceptually match the colour of the reference ring.

3.3 Experimental procedure

The task of the observers was to match the test ring to the reference ring by adjusting the colour of the test ring on the MacLeod and Boynton colour space with the gamepad. This colour space has two chromatic channels (l and s) and one luminance channel (Y) [27].

The steps to perform the task were:

1. Subjects adapted during three minutes in the dark environment.
2. The stimulus was presented and the subject performed the task.
3. A black frame was presented during 5 seconds to reduce the image after-effect.
4. Iterate to step two until all stimuli were matched.

The 16 stimuli (8 colour conditions × 2 spatial frequencies) were presented to the observer in a random order. Subjects performed 12 matches for each condition. They performed an initial training session to familiarise themselves with the task. The results of the matches were stored in a calculus sheet. A copy of the more relevant results variables was stored in a mat file to facilitate faster access to analyse this data.

3.4 Observers

The experiments were preformed by 23 subjects, 8 migraineurs with aura (MA), 8 migraineurs without aura (MO) and 7 non-migraineur control (C) subjects. All had normal or corrected to normal acuity and colour vision was evaluated by Ishihara's test [28] and the D-15 Farnsworth Dichotomous test [29]. Migraine subjects were diagnosed according to the criteria of the International Headache (see the form in Appendix). Controls did not suffer neurological symptoms or primary headache satisfying the IHS classification criteria [30].

3.5 Outliers detection and extraction

Two subjects, a MA and a MO, were excluded from the analysis since their values exceeded the limit values of induction that could be achieved in most of the conditions.

The outliers intrasubject's data were detected by the interquartile range measure (being $Q1$ the median of the lower half of the data distribution and $Q3$ the median value of the upper half). The interquartile range results from the product of the difference between these two values and a constant σ. The greater the sigma value, the less restrictive the measure. In this case $\sigma = 3$, obtaining an lower limit of $Q1 - 3 * (Q3 - Q1)$ and a upper limit equal to $Q3 + 3 * (Q3 - Q1)$.

3.6 Statistical analysis

To compare the psychophysical results of the three groups a statistical analysis using Statistica software was performed. Since subjects evaluated 12 times the same stimuli a nested ANOVA (Analysis of Variance) was performed to test if the difference between three groups was statistically significant. When the nested ANOVA indicated that there existed a significant difference, a Fisher Least Significant Difference post-hoc analysis was used to know which groups had differences. We defined the significance level at $p = 0.05$.

Therefore, when $p < 0.05$ in any of the lsY channels, we could consider that the two groups are significantly different.

3.7 Results

The experimental results are shown in Fig. 3 (striped surround) and Fig. 4 (uniform surround). These figures only show the chromatic plane, i.e. l and s axes. The reference ring, first inducer and second inducer are represented with an open black circle, square and triangle, respectively, joined with dashed lines. Subjects modify the colour of the test ring (initially, the same as the reference ring -open circle-) to match the colour of the test and comparison ring, obtaining a final colour value. This matched colour is represented on the chromatic plane by red, green and blue dots for MO, MA and C groups, respectively. Error bars show the standard error of means. The two visual frequencies are shown with coloured filled circles (lowest frequency) and triangles (highest frequency).

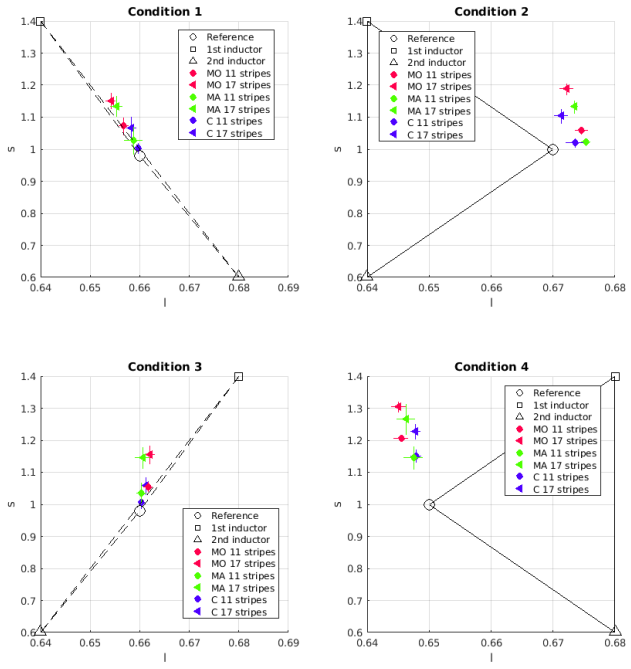


Fig. 3: Psychophysical results for the three groups (MA green, MO red, C blue) on the striped surround conditions. The open symbols indicate the inducers' and test rings chromaticities.

The experimental results show clear differences in induction between the three groups (MA, MO and C).

3.7.1 Striped surround in s axis

Considering only the s axis of conditions 1-4, red (MO) and green (MA) points are closer (higher s values) to the first inducer (open square) than the blue ones (C). These differences are statistically significant with $p < 0.01$. It means that migraineurs have more assimilation than control subjects. Concretely, MO show the strongest assimilation for these four striped conditions.

The three groups show more assimilation in condition 2 than in condition 4. We would expect a symmetry between those conditions in the s axis as appears in conditions 1 and 3.

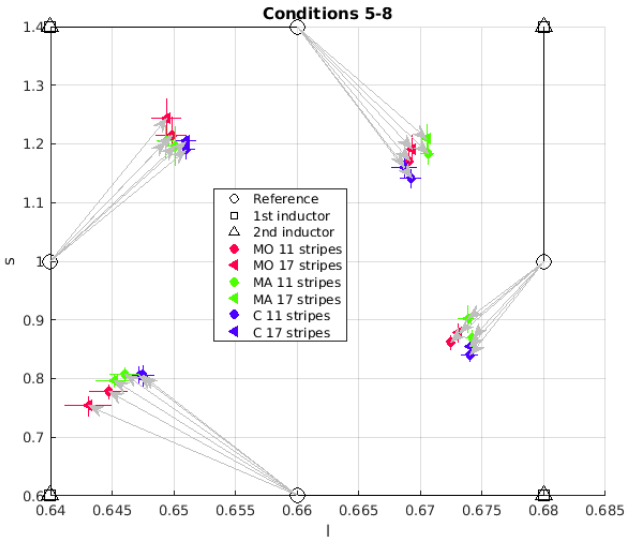


Fig. 4: Psychophysical results for the three groups (MA in green, MO in red, C in blue) on the uniform surround conditions. The open symbols indicate the inducers' and test rings chromaticities.

3.7.2 Striped surround in l axis

In the case of the l axis, we can see in condition 3 that there is no assimilation along this axis, i.e. the red, green and blue dots have the same l value than the reference ring (open circle). In contrast, in condition 1 this dots are closer in the l axis to the first inducer, i.e. the subjects had assimilation along this axis. We would expect the same behaviour for red ($l > 0.66$) and green ($l < 0.66$), i.e. a symmetrical behaviour for this axis around central chromatic colour ($l = 0.66$). This asymmetry suggests that the processing of these two colours is performed by different mechanisms.

3.7.3 Uniform surround

Uniform surrounds results, conditions 5-8, are shown in Fig. 4. Although, in each condition the differences between groups are statistically significant, ($p < 0.05$), none of the three groups systematically shows more contrast than the others.

4 Computational Simulations

4.1 CIWaM model

One of the computational models that tries to reproduce colour processing in the visual cortex and simultaneously reproduce psychophysical results is CIWaM [4]. This model is an extension of a previously published Brightness Induction Wavelet Model (BIWaM) [31]. Moreover, it has been shown that reproduces results of psychophysical experiments on colour induction [4].

CIWaM generates a perceptual image I_c^P defined by

$$I_c^P = \sum_{\nu=1}^{n} \sum_{o=v,h,d} \alpha_{o,c}(\nu, r) \cdot \omega_{\nu,o,c} + c_n \,, \qquad (1)$$

where $\omega_{\nu,o,c}$ is the wavelet coefficient of visual frequency ν and orientation o, with $o = \{v, h, d\}$ being v, h and d vertical, horizontal and diagonal orientations, respectively. The subindex c is related to the three (l, s, Y) channels of the McLeod and Boyton colour space. Visual frequency is expressed as the number of alternating colours per degree of visual angle divided by two, while spatial frequency refers to the specific wavelet planes on which the eCSF is computed and it is expressed in physical units (pixels).

The key factor of this model is the term $\alpha_o(v, r)$, named *extended contrast sensitivity function* (eCSF). It modifies the coefficients obtained from the wavelet decomposition of the visual stimuli and it is responsible for reproducing the induction effects. This function generalises the human contrast sensitivity function (CSF) [32] (which describes the response of the visual system for each visual frequency) by adding a variable r describing the ratio between the center and surround feature contrast. It implies that the CSF is a particular case of the eCSF when the ratio is equal to 1. The eCSF is defined as

$$\alpha(\nu, r) = \begin{cases} z_{ctr} \exp\left(-\frac{\left(log_2 \frac{4}{\nu}\right)^2}{2\sigma_{1,c}^2}\right) + \alpha_{min}, & \nu \geq \nu_{0,c}; \\ z_{ctr} \exp\left(-\frac{\left(log_2 \frac{4}{\nu}\right)^2}{2\sigma_{2,c}^2}\right) + \alpha_{min}, & \text{otherwise} \end{cases}; \tag{2a}$$

with

$$\alpha_{min}(\nu, r) = \begin{cases} B_c \cdot \exp\left(-\frac{\left(log_2 \frac{4}{\nu}\right)^2}{2\sigma_{3,c}^2}\right), & \nu \geq \nu_{0,c} - \gamma_c; \\ B_c, & \text{otherwise}; \end{cases}, \tag{2b}$$

and

$$z_{ctr} = A_c \cdot \frac{r^2}{1 + r^2}, \tag{2c}$$

where σ is the visual angle, and $\nu_0 = 4$ cpd is the peak of the human CSF. Following Otazu et al. [4] we use $\sigma_{1,c} = 2.267526$, $\sigma_{2,c} = 0.895537$ and $\sigma_{3,c} = 2.755627$. Variable $r = \sigma_{cen}^2 / \sigma_{sur}^2$ helps to model the influence of surrounding image features on the perception of a central stimulus. Central stimulus contrast is measured by $\sigma_{cen}^2 = \sum_{\forall i \in \Phi_c} \omega_i^2$, where i is the i-th wavelet coefficient and Φ_c is a window around the central stimulus with diameter $d_{cen,c}$. Surround contrast is measured by $\sigma_{surr} = \sum_{\forall i \in \Psi_c} \omega_i^2$, being Ψ_c a window around the central Φ_c with diameter $d_{sur,c}$. The shape of Φ_c and Ψ_c center and surround windows is shown in Fig. 5. The shape of these windows is a linear mask with spatial orientation o.

(a) (b) (c)

Fig. 5: The center (green) and surround (blue) masks for (a) horizontal, (b) vertical and (c) diagonal orientations of the eCSF.

CIWaM processes independently the luminance and the chromaticity. The two chromatic channels (l and s) use the same set of parameters for the eCSF expression, while brightness Y uses another set [4].

4.2 CIWaM parameters fitting

Since the psychphysical results are different for each group, we can fit the eCSF parameters to these three datasets. The differences between these these three parameters fits could shed light on the different low-level processing between these three populations.

The measure to minimise the fitting function is the difference between the psychophysical results and the computational simulation of those psychophysical experiments.

The steps performed to computationally simulate a psychophysical observation are:

1. For each condition:
   (a) Present a stimulus to CIWaM to obtain a computational estimation of the perceived colours.
   (b) Modify the test ring colour to match the reference one according to the perceptual CIWaM estimation.
   (c) Iterate through (a) and (b) until the perceptual difference between the test and the reference rings is lower than a given threshold.

The algorithm used to fit the parameters has been a non-linear curve-fitting solver: *lsqcurvefit* MATLAB routine [33].

This parameter fitting process was accelerated with a parallelisation of the 8 different chromatic configurations on the cluster of the Departament de Ciències de la Computació (UAB).

Several sets of parameters have been optimised. Following, we show them grouped in three categories:

– Chromatic channels (l, s) share the same parameters:
  1. Center and surround window size: (d_{cen}, d_{sur}).
  2. eCSF parameters without center and surround: $(A_c, \sigma_1, \sigma_2, \sigma_3, \gamma_c, B_c)$.
  3. All eCSF parameters: $(A_c, \sigma_1, \sigma_2, \sigma_3, \gamma_c, B_c, d_{cen}, d_{sur})$.

– Different parameters for each chromatic channel (l, s):
  4. Center and surround window size: $(d_{cen,l}, d_{sur,l}, d_{cen,s}, d_{sur,s})$.
  5. All eCSF parameters: $(A_{c,l}, \sigma_{1,l}, \sigma_{2,l}, \sigma_{3,l}, \gamma_{c,l}, B_{c,l}, d_{cen,l}, d_{sur,l}, A_{c,s}, \sigma_{1,s}, \sigma_{2,s}, \sigma_{3,s}, \gamma_{c,s}, B_{c,s}, d_{cen,s}, d_{sur,s})$.

– Frequency based:
  6. Center and surround window size: $(d_{cen,l,\nu}, d_{sur,l,\nu}, d_{cen,s,\nu}, d_{sur,s,\nu})$.
  7. Scalar eCSF: $eCSF_\nu$.

The $eCSF_\nu$ substitutes the $eCSF$ with a single scalar value that is multiplied to the wavelet plane.

4.3 Computational simulation results

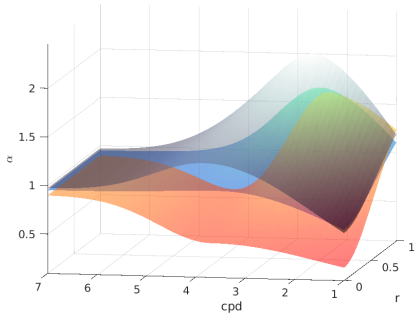
In this section we only show results of some fits (fits number 4, 5 and 7).

Fit #4 considers different center and surround window sizes for the two chromatic channels (l, s) (see predictions in Fig. 10 and 11). For conditions 1-4, CIWaM-based computational simulations generate weak assimilation on the *s* axis for the three groups. In the *l* axis and condition 1 the simulated assimilation is similar to psychophysical results, but in condition 3 computational simulation generates too much assimilation. The reason is that CIWaM is a linear model, and it generates the same results for red ($l > 0.66$, condition 3) and green ($l < 0.66$, condition 1) colours. Since no assimilation is observed from psychophysical experiments in *l* axis in condition 3, CIWaM cannot correctly reproduce this asymmetry in l axis. For conditions 5-8, computational simulations generate weak contrast on both chromatic axes. Three different starting values for the center and surround windows sizes were used for this optimisation (Table 1). Despite each case finished in a different local minimum, the results of the computational simulation of psychophysical experiments were quite similar. We can conclude that these parameters (d_{cen}, d_{sur}) do not play a major role in the computational simulation or that there is not a representative global minimum.

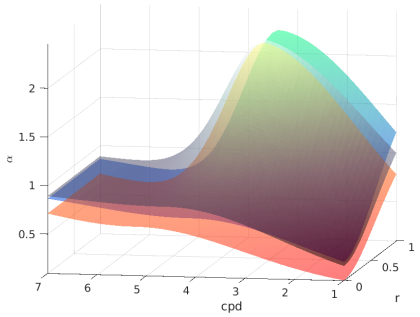
	Initial values: $d_{cen,l} = 3, d_{sur,l} = 15$, $d_{cen,s} = 3, d_{sur,s} = 15$			
	l		*s*	
Groups	d_{cen}	d_{sur}	d_{cen}	d_{sur}
MA	1	7	1	3
MO	1	11	1	3
C	1	3	1	3
	Initial values: $d_{cen,l} = 1, d_{sur,l} = 3$, $d_{cen,s} = 1, d_{sur,s} = 3$			
	l		*s*	
	d_{cen}	d_{sur}	d_{cen}	d_{sur}
MA	4	10	4	6
MO	3	11	4	6
C	3	5	5	9
	Initial values: $d_{cen,l} = 5, d_{sur,l} = 15$, $d_{cen,s} = 5, d_{sur,s} = 15$			
	l		*s*	
	d_{cen}	d_{sur}	d_{cen}	d_{sur}
MA	5	9	5	15
MO	5	15	5	7
C	5	9	5	11

TABLE 1: CENTER AND SURROUND WINDOW SIZES (IN PIXELS) FOR THE THREE DIFFERENT STARTING WINDOW SIZE VALUES.

Fit #5 considers different eCSF parameters for the two chromatic channels (l, s) (see predictions in Fig. 13 and 14). For conditions 1-4, computational simulations generate weak assimilation on the *s* axis for the three groups. In the *l* axis and conditions 1 and 3, MO and C simulations show assimilation, while the computational simulation for MA always generates contrast for *l* axis. For conditions 5-8, the simulation generates weak contrast for MO and C on the *l* axis, however, the *s* axis results are well approximated. The



(a) l channel



(b) s channel

Fig. 6: Extended contrast sensitivity functions for the two chromatic channels. Orange surface plot: MA, grey surface plot: MO, blue surface plot: C.

MA simulation is similar to psychophysical results on both axes. This optimisation has been performed with three different starting values for center and surround window sizes. However these values were barely altered from the starting ones, which implies that they are not relevant in the eCSF.

The eCSFs of the three populations (Fig. 6) are very similar in the *s* channel. However, migraineurs (MA and MO) have lower values than C, as expected from the results from other authors [34] (Fig. 8). In the *l* channel, the eCSFs maximum for the three groups, that would be expected between 3 and 4 cpd, is obtained at 2 cpd. Moreover, for the three initial window size value sets the fits generate different eCSFs, but they obtain similar psychophysical simulation results. Specifically, the discrete values of r and ν in which the experiments have been developed are divergent for each group and initial window size values. These results show that CIWaM is not able to adjust to the *l* channel since it is based in the flawed assumption, as seen from psychophysical results, that the *l* channel is symmetric.

Fit #7 considers a $eCSF_\nu$, i.e. a multiplicative value for each wavelet plane and chromatic channel (l, s). This approximation cannot process spatial information to induce assimilation and contrast. Nevertheless, this fit generates the most accurate results in all conditions for both chromatic axes (l, s) (see Fig. 15 and 16).

The multiplicative values (Fig. 7) on the *s* channel show a similar profile as the results of [34] where non-migraineurs (C) have a contrast sensitivity function (CSF) greater than migraineurs (MA and MO). On the *s* channel, due to its asymmetry, the multiplicative values do not lead to conclusive results.

In conclusion, the best simulation results are achieved by

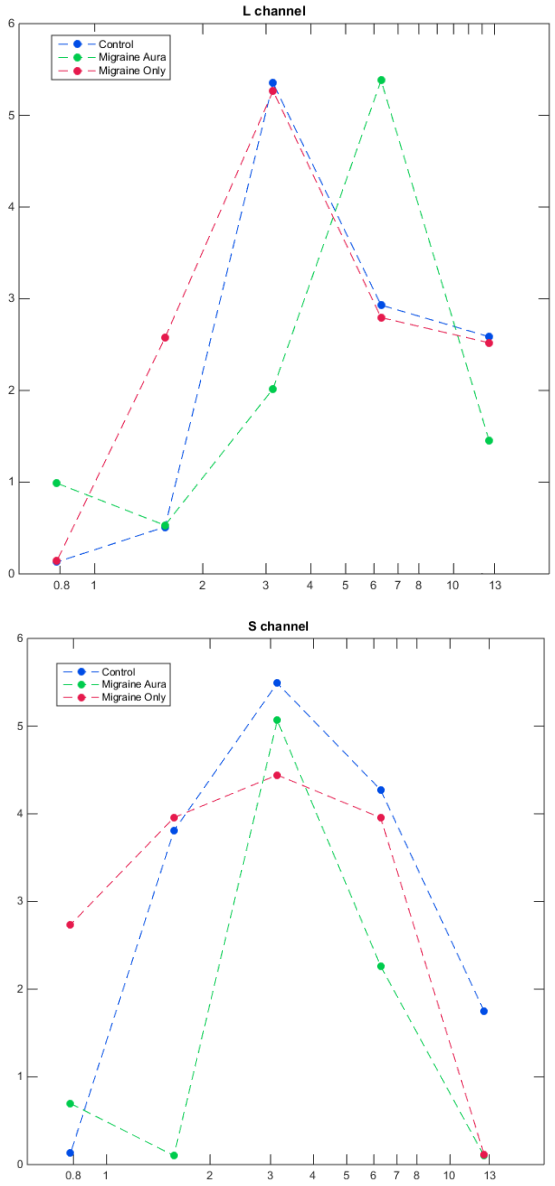


Fig. 7: Multiplicative factor value for the seven wavelet planes of *l* channel and *s* channel.

fit #7 ($eCSF_\nu$). Nevertheless, since the psychophysical results of conditions 1 and 3 and conditions 2 and 4 had asymmetries in the *l* axis and CIWaM did not take into account the polarities of the channels, the adjustment to the *l* channel was not accurate. The *s* channel shows similar results. Since, we did not perfomed psychophysical experiments with striped surrounds for the lime inducer (negative polarity of the *s* channel) CIWaM parameters were not fitted for these data. It simplified the simulations and fittings for this axis without taking into account the possible asymmetries. All in all, these results show that CIWaM is not a good colour induction model since it does not take into account the chromatic differences inter- and intra-channel.

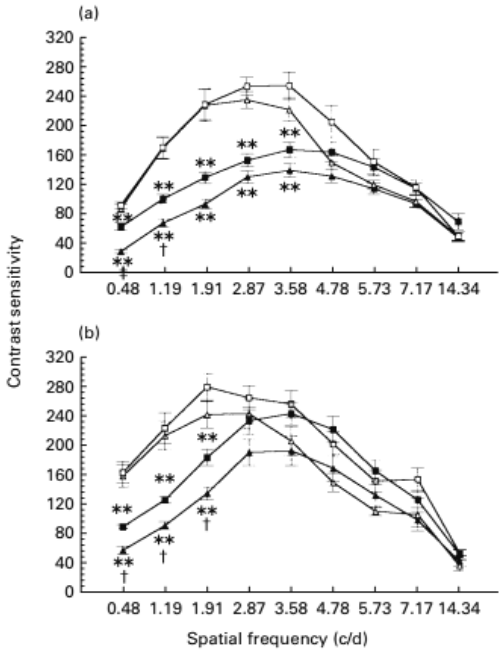


Fig. 8: Benedek et al. [34] results of photopic contrast sensitivity of migraineur (full symbols) and non-migraineur (open symbols) estimated with (a) static stimulation (b) dynamic method.

5 Conclusions

The initial hypothesis was that both MA and MO have an hyperexcitabillity of the visual cortex associated with the reduction in neural inhibition or habituation, as seen by [17, 19, 35–40]. This would imply a reduction in colour assimilation and, in consequence, an enhancement of contrast induction.

The experimental results do not go in line with this hypothesis since it has been observed that both MA and MO have more assimilation than C in the two chromatic channels (l, s). Migraineurs results also show more contrast than C in the majority of the conditions. This implies that the proposed altered mechanism does not give an explanation to these results.

On the other hand, the simulation results show that CIWaM does not reproduce the psychophysical results because it processes equally the two chromatic channels (l, s). Moreover, it does not take into account the polarities of these channels, which have only been psychophysically studied (in the *l* channel), and we found in this axis that they are not symmetric.

6 Future work

A more extended study on colour induction in migraineurs is needed. There only exist studies on colour discrimination and colour vision [17, 20, 37], therefore different experiments can be done in migraine people to study the differences in colour induction. Moreover, these psychophysical experiments should be extended with assimilating conditions that stimulate the negative polarity of the *s* axis.

On the other hand, CIWaM should be modified to separate the parameters of the two chromatic channels (l, s)

and their polarities. This will achieve more accurate results since the differences in induction for the two chromatic channels and the polarity difference in the *l* channel could be taken into account.

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APPENDIX

1.1 International Headache Society criteria

Migraine without aura

A. At least five attacks fulfilling criteria B–D

B. Headache attacks lasting 4–72 hours (when untreated or unsuccessfully treated)

C. Headache has at least two of the following four characteristics:

(1) unilateral location

(2) pulsating quality

(3) moderate or severe pain intensity

(4) aggravation by or causing avoidance of routine physical activity (e.g. walking or climbing stairs)

D. During headache at least one of the following:

(1) nausea and/or vomiting

(2) photophobia and phonophobia

E. Not better accounted for by another ICHD-3 diagnosis.

Migraine with aura

A. At least two attacks fulfilling criteria B and C

B. One or more of the following fully reversible aura symptoms:

(1) visual

(2) sensory

(3) speech and/or language

(4) motor

(5) brainstem

(6) retinal

C. At least three of the following six characteristics:

(1) at least one aura symptom spreads gradually over 5 minutes

(2) two or more aura symptoms occur in succession

(3) each individual aura symptom lasts 5–60 minutes

(4) at least one aura symptom is unilateral

(5) at least one aura symptom is positive

(6) the aura is accompanied, or followed within 60 minutes, by headache

D. Not better accounted for by another ICHD-3 diagnosis.

1.2 Experiments stimuli

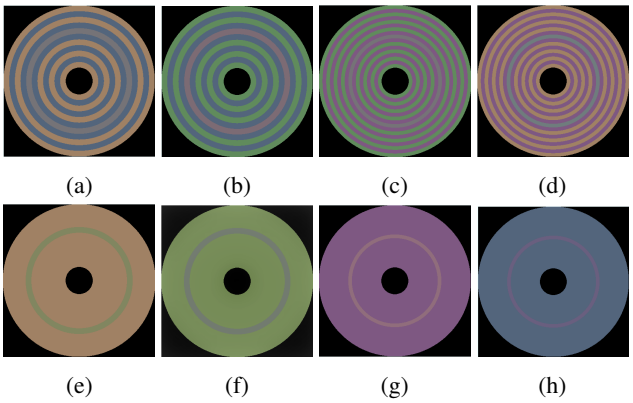


Fig. 9: The chromaticities of the inducers generate (a-d) striped surrounds when they are different and (e-h) uniform surrounds when they have the same colour. (a,b,e,f) have patterns with the lowest spatial frequency configuration and (c,d,g,h) have the highest spatial frequency patterns.

1.3 CIWaM prediction results

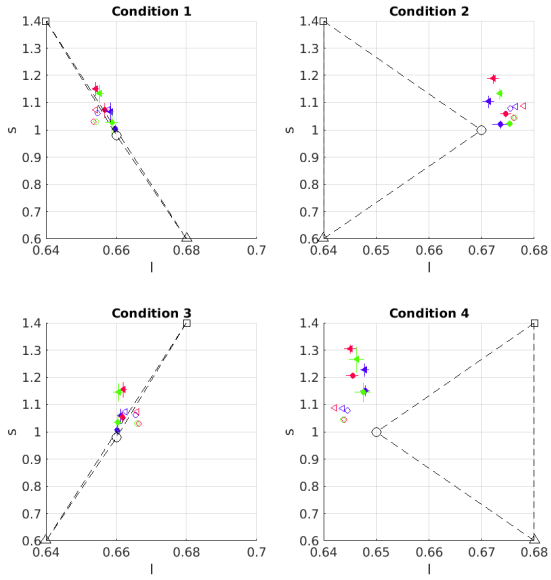


Fig. 10: CIWaM predictions for the center and surround optimisation with separate variables for the two chromatic channels (Fit #4) compared with the psychophysical results for the three groups on the striped surround conditions.

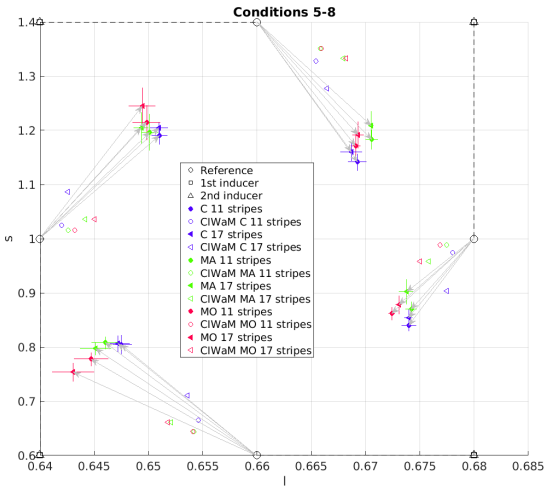
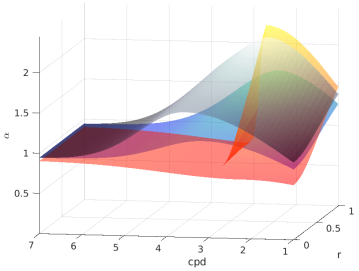
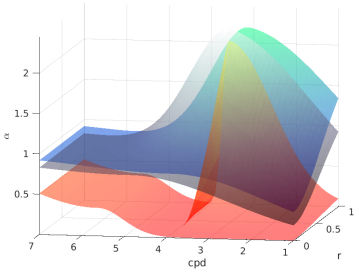


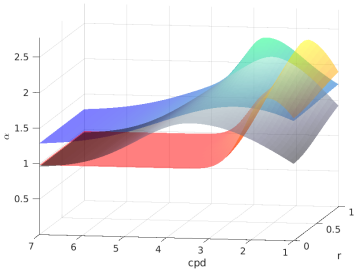
Fig. 11: CIWaM predictions for the center and surround optimisation with separate variables for the two chromatic channels (Fit #4) compared with the psychophysical results for the three groups on the uniform surround conditions.



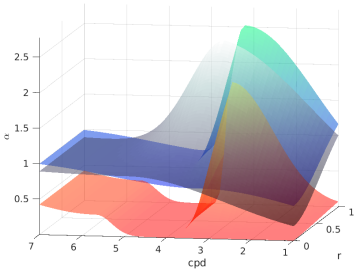
(a) l channel, initial values: $d_{cen,l} = 3, d_{sur,l} = 15$



(b) s channel, initial values: $d_{cen,s} = 3, d_{sur,s} = 15$



(c) l channel, initial values: $d_{cen,l} = 5, d_{sur,l} = 15$



(d) s channel, initial values: $d_{cen,s} = 5, d_{sur,s} = 15$

Fig. 12: Extended contrast sensitivity functions for the two chromatic channels of fit #5. Orange: MA, grey: MO, blue: C.

	Initial values: $d_{cen,l} = 3, d_{sur,l} = 15$, $d_{cen,s} = 3, d_{sur,s} = 15$							
	l channel							
Groups	d_{cen}	d_{sur}	σ_1	σ_2	σ_3	γ	A_c	B_c
MA	3	1	0.1111	1.5454	2.9782	-0.4663	2.9736	0.0000
MO	3	1	0.8731	1.5109	2.6376	0.9408	1.2874	0.0000
C	3	1	0.9041	1.5935	2.6969	0.5020	1.0426	0.0000
	s channel							
	d_{cen}	d_{sur}	σ_1	σ_2	σ_3	γ	A_c	B_c
MA	5	1	0.1242	1.0524	0.5959	2.9709	4.0349	0.0000
MO	4	2	0.9224	2.0806	2.3162	2.2375	3.0389	0.0000
C	4	1	0.8962	2.3786	2.2549	1.2291	2.8905	0.0000
	Initial values: $d_{cen,l} = 1, d_{sur,l} = 3$, $d_{cen,s} = 1, d_{sur,s} = 3$							
	l channel							
	d_{cen}	d_{sur}	σ_1	σ_2	σ_3	γ	A_c	B_c
MA	1	1	0.8277	2.0772	2.2925	1.0272	2.4649	0.0000
MO	1	1	0.9589	1.5520	2.2870	1.2028	1.8388	0.0000
C	1	1	0.8982	1.5064	2.6049	0.8783	1.4950	0.0000
	s channel							
	d_{cen}	d_{sur}	σ_1	σ_2	σ_3	γ	A_c	B_c
MA	1	3	0.7842	1.9723	2.2183	2.5931	3.2794	0.0000
MO	1	2	0.8204	2.3491	2.3275	1.9586	2.7781	0.0000
C	1	2	0.7430	2.2537	2.3339	1.4659	3.1482	0.0000
	Initial values: $d_{cen,l} = 5, d_{sur,l} = 15$, $d_{cen,s} = 5, d_{sur,s} = 15$							
	l channel							
	d_{cen}	d_{sur}	σ_1	σ_2	σ_3	γ	A_c	B_c
MA	3	2	0.4072	1.1853	1.1970	-0.9964	1.0078	0.0000
MO	4	5	0.8280	1.2899	2.7146	0.7867	1.1442	0.0000
C	3	4	0.4266	0.7701	2.9854	-0.2997	1.0060	0.0000
	s channel							
	d_{cen}	d_{sur}	σ_1	σ_2	σ_3	γ	A_c	B_c
MA	5	1	0.1182	0.9992	0.3491	2.9994	3.4385	0.0000
MO	5	4	0.8271	2.2548	2.3404	2.3168	3.1343	0.0000
C	5	6	0.2930	1.5744	2.6017	0.5719	3.6381	0.0000

TABLE 2: ALL eCSF PARAMETER RESULTS OF FIT #5. CENTER AND SURROUND SIZE VALUES IN PIXELS.

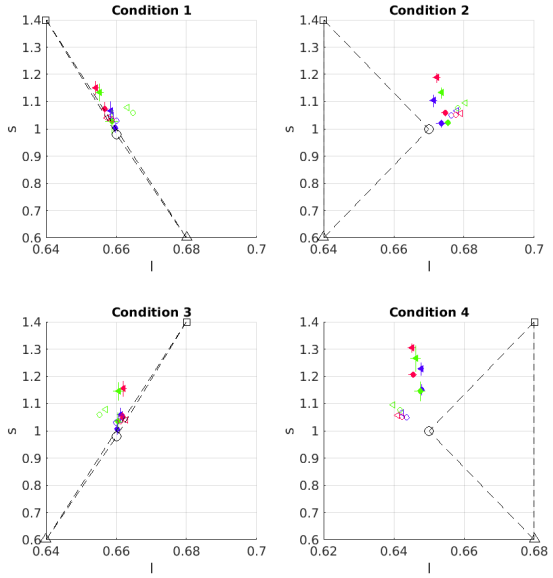


Fig. 13: CIWaM predictions for all the eCSF parameters optimisation with separate variables for the two chromatic channels (Fit #5) compared with the psychophysical results for the three groups on the striped surround conditions.

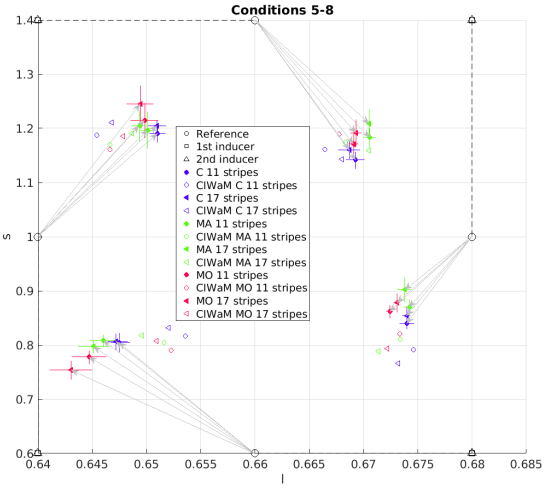


Fig. 14: CIWaM predictions for all the eCSF parameters optimisation with separate variables for the two chromatic channels (Fit #5) compared with the psychophysical results for the three groups on the uniform surround conditions.

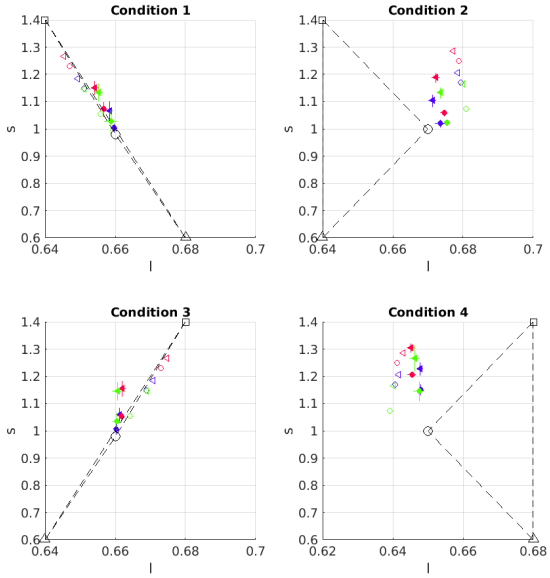


Fig. 15: CIWaM prediction adjusting a $eCSF_\nu$ instead of the eCSF for each channel and wavelet plane (Fit #7) compared with the psychophysical results for the three groups on the striped surround conditions.

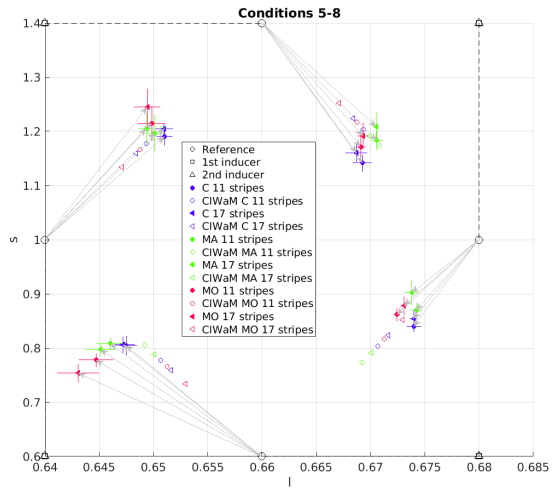


Fig. 16: CIWaM prediction adjusting a $eCSF_\nu$ instead of the eCSF for each channel and wavelet plane (Fit #7) compared with the psychophysical results for the three groups on the striped surround conditions.