IRP
Simulating the McCollough Effect
in a Self-Organizing Model of the Primary Visual Cortex

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Abstract

The McCollough effect, an orientation-contingent color aftereffect, constitutes a useful tool to study the functionalities of the visual system. There have been several attempts to model and understand the neural mechanisms underlying it, but none of them give a satisfactory functional explanation of the effect. Moreover, numerous experiments seem to indicate that this aftereffect involves the primary visual cortex (V1), and there have been no reported efforts to simulate it with a computational model of this cortical area. The present document constitutes an original proposal for performing a computational study of the McCollough effect with a self-organizing map model of V1, and clarifying the neural mechanisms giving rise to it.

1 Purpose

1.1 Background

The McCollough Effect (hereafter ME) is a visual aftereffect discovered in 1965 by Celeste McCollough [1]. It involves two stimulus dimensions, color and contour orientation, and is therefore traditionally described as an orientation-contingent color aftereffect. To experience the effect, one has to look for few minutes at red-and-black horizontal gratings alternating with green-and-black vertical gratings. Then, similar black and white gratings will appear greenish afterwards when horizontal, and pinkish when vertical (see figure 1 to experience the effect). As with other visual aftereffects, the ME is a useful psychophysical tool for probing the human visual system and particularly for studying interacting properties between orientation coding and color perception.

The ME has been the subject of a large body of literature and of numerous experiments about its properties and theoretical accounts. Concerning the processing level involved in the effect, much evidence suggests that it arises in the primary visual cortex (V1) [2, 3, 4, 5], but the nature of the neural mechanisms underlying it are far from being clear. There have been several attempts to develop neural networks for studying the ME and testing theoretical assumptions about it. Nevertheless, there has been no satisfactory functional explanation based on a model of the ME and no reported efforts to simulate it with a computational model of V1.

LISSOM (Laterally Interconnected Synergetically Self-Organizing Map) is a biologically plausible, self-organizing map model of V1. Fundamental assumptions of this model are that lateral connections between cortical neurons have an important role in cortical processing and that it self-organizes through Hebbian learning. It has already successfully accounted for important anatomical and functional features of V1 such as the input-driven development of topographic, ocular dominance, orientation and motion direction maps as well as the development of patchy lateral connectivity [6, 7, 8]. It has also been used to perform a successful computational study of another visual illusion,
the tilt-aftereffect [9, 10], and so has demonstrated its capacity to probe adult visual perception. The model has recently been extended further to include the ON and OFF channels of the LGN, dichromatic (red and green) color processing in the retina and LGN, and has been shown to develop “blobs” of laterally connected color selective cells within the orientation map [11]. The observed blobs and receptive fields are similar to those found experimentally in the cortex [12]. Therefore, this extended model seems to be appropriate to simulate and study the ME since it provides the required interaction between color and orientation coding in an already strongly assessed model of V1.

1.2 Objective

The objective of this project is to demonstrate that a self-organizing model of orientation and color maps in V1 can exhibit the ME, and by doing so clarifying the functional mechanisms giving rise to it. A computational study of the effect will therefore be performed using the LISSOM model of the primary visual cortex. More than just leading to a better understanding of the ME, this will also enable further exploration of the neural network model’s functional behavior, and might lead to a better understanding of the basic processes underlying color and orientation perception.

2 Previous attempts to simulate the ME with neural networks

Using a computational model can be really useful to investigate cognitive phenomena that are difficult to understand experimentally. Therefore, there have been several attempts to account for the ME using neural networks. They generally focus on different properties of the ME and so none of them lead to a model verifying them all. Moreover, either they are models developed in order to specifically explain the ME within the framework of more general functional theories of visual processing, or they are of too minimal complexity to be realistic.

Three neural networks have been developed to test elaborate theories stating that the ME is produced by two functional components: edge color and spread color [13], or boundary and surface representations [14, 15]. Both link the ME to the phenomena of color constancy, correction of achromatic aberation and the filling-in process [16, 13, 14, 15]. They all involve attractive theories, but require a complicated and specific neural network to be demonstrated. Firstly, it is difficult to do large scale simulation with such networks and secondly they are not the representation of a specific cortical area but involve different types of cells all along the visual pathway.

Two others neural networks that aim to model the ME - including the first attempted one by Montalvo (1976) [17] - are extensions of feature-extracting networks applied to the ME. The more recent one is based on sources separation and uses Independent Component Analysis to perform learning [18]. It gives an interesting view of the neural mechanisms underlying the basic processing of color and orientation, and its approach and network structure are closer to LISSOM’s ones. Nevertheless, both of these networks are of really minimal complexity and are far from being realistic models of the visual cortex. Consequently, they neither give a satisfactory explanation of the ME nor include it within a more general theory.

Instead, LISSOM is one of the most advanced self-organizing map models of the primary visual cortex, and has already led to a better understanding of V1’s structural development and information processing [7, 8, 6, 9, 11]. Thus, if the model is shown to exhibit the effect, it would give an interpretation of the ME which would be part of a more general theory that aims to model the global organizational structure of V1. The fact that using this model to study the tilt-aftereffect leads to the conclusion that the effect results from the Hebbian learning of the strength of lateral
Figure 1: The McCollough Effect. To experience the effect gaze at the two coloured patterns for a few minutes, switching back and forth now and then without staring at a particular point. Note that it really works better if you do it for at least 5 minutes. Return to the first black and white pattern. You should see the horizontal pattern ‘greenish’ and the vertical one ‘pinkish’. Now, if you rotate the sheet by 45°, it will you look white again; by 90° the colours will exchange places on the gratings. It is also interesting to try to see it again in an hour to experience the duration of the effect.
inhibitory connections between neurons, gives rise to the hope that similar mechanisms underlie the ME. Furthermore, visual effects (as well as interactions between sensory dimensions) are typically constraints that a computational model of the visual system should respect, and the LISSOM model would be validated further if it could exhibit the ME.

3 Methods and Techniques

This section describes the methods and techniques intended to be used for performing the proposed computational study of the ME.

3.1 Method for Measuring Perceived Color

In order to assess and compare the ME in LISSOM with human psychophysical experiments, a method for measuring the perceived color in the model needs to be developed. In other words, given a pattern of activation in V1, an estimate of the input’s color needs to be computed. This has already been done for the orientation dimension of the map when studying the tilt-aftereffect, but the program does not implement such a measure for the color dimension. Thus, a relevant method has to be chosen and implemented to perform this measurement.

It seems likely that a similar method to the one used for orientation can be applied to color. How the perception of a given dimension is coded in the cortex is not understood yet, but one of the common assumptions is that the value of a particular sensory dimension, such as orientation, is represented by the group of neurons in V1 that are tuned for this dimension. Moreover, experiments on V1 neurons in monkeys suggest that they use a statistical encoding of orientation [19]. Thus, the perceived value of color in the model can also be determined by computing a weighted average over the color preferences of all color-selective neurons activated for a given input.

In order to give map representations of V1, the system already implements a method to determine the preference of a neuron for a given sensory dimension (e.g., orientation, phase, spatial frequency). Concerning the color map, preferences have only been determined in terms of green or red channel selectivity. Therefore, a hue and saturation color preference measure has to be set for obtaining a more detailed color map. The same method as for orientation can be applied with a hue and saturation scale instead of an orientation one. The program also generally implements a method to give an estimate of the perception for a given dimension and a given input, but it has not been done yet for color.

In the case of a stimulus having an acyclic measurement (e.g., spatial frequency) the perceived value is a simple weighted average over preferences of all neurons tuned for this stimulus dimension. In the case of a cyclic stimulus like orientation (orientation repeats every 180°, hue of perceived color repeats every 360°), a neuron’s preference has to be represented as a vector such that the representation for the lower value on the scale is the same as for the higher one (0° has the same representation as 180° and the long wavelength of red looks similar to the short one of violet). The perceived value for this sensory dimension is further computed as a weighted sum over all neurons’ preferences, where the weight represents the activation level of the neuron. This method for measuring cyclic values has been shown to be statistically significant under conditions present in the model [20].

Thus, a similar method can be used for computing neurons’ hue and saturation preferences, obtaining a more detailed color map and estimating perceived color in the model. The vector sum method being already implemented in the model, little programming effort appears to be required to add this functionality. In order to verify that such measurement leads to accurate results for estimating perceived color, the method must also be assessed by presenting different uniformly colored
input, computing the estimate and comparing to the real value of the input.

### 3.2 Experimental setup

The LISSOM model is composed of several neural units’ sheets modeling the visual pathway from the retinal photoreceptor to V1. It has been primarily used for simulating the input-driven self-organization of V1 in color and orientation maps [11] (as well as ocular dominance, direction, and spatial frequency maps). The self-organization in maps of features is the result of an Hebbian learning process highly active during the training stage simulating the early development of the cortex. When this training is over and the map formed, the model can be used to investigate phenomena in the adult cortex. In order to simulate the cortical plasticity observed in adult cortical structures, learning still occurs but at a much lower rate than during the development process. This is this cortical plasticity which gives rise to the effect in the tilt aftereffect simulation, by modifying the lateral interactions (more precisely by increasing inhibition) between neurons having preference for the orientation used during induction, resulting in a “shifted” representation of the orientation of the test input.

Therefore, the final state of the orientation and color maps model of V1 obtained in the previous simulation can be used as a starting point for studying the ME [11]. Then, a reasonable experiment has to be set up in order to simulate the induction and the test stage of the effect. During the induction stage, the induction pattern of the ME has to be presented to the model (an alternation of red-and-black horizontal gratings and green-and-black vertical gratings), while learning occurs. The test stage is the presentation of the test pattern (white and black horizontal and vertical gratings) and the measurement of the perceived color. Obviously, a pre-induction test must also be done to check that there is no perceived color measured before induction.

In order to start this experiment, some parameters have to be set:

- The time of exposure during induction and the frequency of the alternation between both induction patterns.
- The value of the color for each induction pattern (on a hue and saturation scale).
- The value of the learning rate parameter driving cortex plasticity.

The first two groups of parameters must obviously be set with respect to the psychophysical experimental values that have been used for testing the ME, because the results of these same experiments will be used to assess the outcome of the simulation. The later parameters should be similar to those used in the tilt-aftereffect experiment [10, 9], in order to obtain consistent results. Nevertheless, they may be inappropriate for simulating the ME and so may have to be set by exploring different parameter values in experiments.

### 4 Evaluating the outcome

One of the important tasks to be done when starting the project is to find precise and relevant psychophysical data to serve as a reference when assessing the simulation. Nevertheless, even though not all the necessary data are presently gathered, the process of evaluating the result of the simulation is already set. It consists of a series of assessments, going from the simple (and principal) hallmark of the ME to more complicated properties.
1. In the first place, the model must exhibit the specific ME responses for both test patterns, following a classical induction with red-horizontal and green-vertical gratings. Obviously, if this simple test stage is never conclusive (i.e. the perceived color remains white), the simulation fails and something has to be done to remedy it (see next section).

2. The ME is a color aftereffect contingent on orientation. So, whatever orientation and colors used during induction (0°-red/90°-green but also -45°-green/45°-red), the complementary color should be perceived when presenting the corresponding test pattern. Therefore, different orientations and combinations can be tested to test the contingency of perceived color with orientation.

No reference has been found to an experiment measuring the amplitude of the effect with respect to the orientation of the induction pattern. The fact that it appears to have more neurons tuned for vertical and horizontal orientations than for intermediate ones (e.g. 45°) in V1 (reflecting the environmental statistic) [7] could produce a stronger aftereffect for these orientations. When the map model is trained with natural images, it reflects the same bias. Therefore, the same effect could be observed in the model. Nevertheless, psychophysical data remain to be found on this subject.

3. Orientation contingency also gives an interesting metric concerning the variation of the perceived color with respect to the orientation of the test pattern. The perceived color decreases to zero when rotating the test pattern to 45°, then changes to the complementary one and increases until 90°. A curve of the color change with respect to orientation has been used obtained from one of the previous neural network simulations [18], but no detailed comparison has been made with psychophysical data. This curve would be a good starting point as a metric to compare the simulated effect with data from human experiments.

4. At this stage finer evaluation can be made using more extensive measurements on the ME:

- The intensity of the effect has been shown to be dependent on the length of time the inducing patterns were present on the retina [21]. Simulations with different induction times can be done and the results confronted with those of psychophysical experiments.

- In the same way, the intensity of the effect is also dependent on the saturation of the color used during induction [16]. Simulations using different levels of saturation can be carried out and the results compared with human experiments.

This evaluation constitutes the first step to follow in order to validate the potential simulated ME, but a more extensive study is further possible and more properties of the ME can be studied as we will examine in the next section.

5 Outcome of the project

The desired outcome of the project is that the model is shown to exhibit the ME. As described above this will be evaluated by examining if the simulated ME presents similar basic features to the ones experienced by humans. In this optimistic (but expected) case, several things have to be done to improve the simulation and gain a better understanding of the effect.

A good model of the ME has to account for more complex properties than those used for primary evaluation. Therefore, it would be very interesting to explore further observations concerning the ME:

- The binocular interactions are unusual for the ME since it does not present interocular transfer for monocular adaptation [1], but can be induced in both eyes by presenting the two dimensions
of the induction pattern (color and orientation) separately in each eye [22]. This could be tested by using the binocular version of LISSOM used to develop ocular dominance map.

- The ME persists for a very long time [23]. The duration properties of the effect could also be explored. The problem is that natural images usually seen by an individual between two measurements of perceived color must also be simulated in the model, which would be highly time consuming.

- An Indirect McCollough effect has been reported in some experimental circumstances and can also be studied by reproducing the same experiment [24].

- Another aftereffect thought to be driven by similar mechanisms to the ME is called the tilt-aftereffect contingent on color and can also be simulated [25].

Moreover, if the model manages to simulate a valid ME, it should be used to perform a functional study of the neural process that gives rise to the aftereffect. The previously obtained results on the tilt-aftereffect give some clues about what mechanisms can produce the ME: the change in strength of lateral connections (and particularly long-range inhibitory ones), during induction of the effect, could reduce the activation of color-selective neurons leading to a complementary perceived color on the corresponding test pattern. Another interpretation could involve neurons tuned to both color and orientation. Such “double-duty” neurons are indeed found in the monkey visual cortex [26, 27], but also in the LISSOM model of V1 [11]. During induction, inhibitory connections between horizontal-green neurons and other green-selective neurons would increase, so that when black and white horizontal test patterns are presented, these neurons tuned for green and horizontal orientation would inhibit green-selective neurons, leading to a redish perceived color. A similar phenomenon would occur for neurons tuned to red and vertical orientation. Such an interpretation would actually lead to the conclusion that the ME is not a flaw of the visual system, but the consequence of the same self-organizing process that drives the development of an efficient sparse distributed representation, and the plasticity of the adult cortex. To verify this interpretation, the learning rate for the different types of connection (excitatory, inhibitory and afferent) can be set in order to explore the separate influence of each one on the ME. In light of such an analysis, the mechanisms underlying the ME can be considerably better understood and linked to more general concepts on the organization of V1. Moreover, it could lead to a better understanding of the processing of color and orientation conjointly.

Even if a lot of previous results and research seems to indicate that such a simulation is likely to be successful, it might happen that it is not. In this case, it could either indicate that the model of V1 is not complete enough to account for the effect, but also that maybe the mechanisms in V1 are not sufficient alone to give rise to the effect. Indeed, there are fMRI studies indicating that the ME correlates with activity in higher cortical areas, suggesting that higher level processes are involved in the ME [28, 29]. In particular, activity in the area V4 (a cortical area believed to be involved in color vision), seems to correlate with the perception of the ME. Therefore, it would be difficult to know the reasons for the failure, but in this case biological evidence will be explored further, and an attempt to modify the model in order to add what could potentially have been missed will be undertaken. For instance, the model could be extended further to include an additional cortical area modeling V4, or the training process could be modified so as to obtain more neurons sensitive to both color and orientation. In any case, the attempted modification should be justified by biological evidence. Moreover, the work done in obtaining more detailed color maps and measuring perceived color will lead to a better understanding of color processing in LISSOM and to an improvement of the model, even if the simulation of the ME is a failure.
6 Workplan

This section roughly describes how I will organize my time to achieve this project.

- **End of May to middle of June**: installation and learning of LISSOM functionalities, detailed searching of the literature, implementation and test of the code for establishing a detailed color map and computing the perceived color for a given input.

- **Middle of June to July**: experimental setup, exploring of different parameter values, experiments and validation of the first set of evaluation.

- **July**: if successful, performing improved and more accurate experiments and analyzing the results. If not, attempting to modify the model and understanding why it failed, potential modification of training process and measurement method, further exploration of the color map model.

- **August**: polishing the experiments and writing the report.

References


