McCollough effect and eye optics

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Abstract. Astigmatism induced by cylindrical lenses leads to colour sensations similar to the McCollough effect. Consequences for the design of experiments and a new interpretation of the McCollough effect are suggested.

1 Introduction
The McCollough effect (McCollough 1965) has usually been interpreted as an adaptation of orientation- and colour-specific edge detectors at the cortical level (McCollough 1965; Creutzfeldt 1973; Lovegrove and Over 1973). We present here some experiments that may shed new light on this interpretation.

The McCollough effect may be evoked by looking alternately at gratings of horizontal green and black stripes and vertical red and black stripes for some minutes. When one looks then at black and white gratings of the same spatial frequency, a pinky shade can be observed between horizontal black stripes and a greenish shade between vertical black stripes. In contrast to other adaptation effects, the McCollough effect is very long lasting.

In evaluating this visual phenomenon, one must take into account the aberrations produced in the eye. Owing to the dispersion of the optic media of the eye, the refractive power of cornea and lens varies considerably with wavelength. Chromatic aberration necessitates an accommodative shift of 1·5 diopters to focus either red or blue light. When one views an edge in white light it is not possible to get a sharp retinal image. Accommodation can only select one wavelength for which the edge is sharp, all other spectral components being out of focus. As a result there are colour fringes parallel to the edge.

In spite of these fringes our visual system is able to make objective colour judgements. To understand this ability one must assume that our central nervous system (CNS) possesses, in every situation, a precise description of the colour fringes produced by chromatic aberration in the eye. Objective colour near the edges can only be perceived as a deviation from this 'expectation'. The chromatic fringes change with certain physical parameters which determine the condition of the eye. The CNS must 'know' the functional dependence of the expected colour fringes on these parameters. If this functional dependence is experimentally manipulated, then the brain can readapt by new learning. Subjects with prisms in front of their eyes report seeing colour fringes in white light, because chromatic aberration is changed and no longer corresponds to the expectation. After a few days of continued exposure to prisms the fringes disappear, showing that the CNS is able to return to changed eye optics (Gibson 1933; Kohler 1962).

In an astigmatic eye (most people have a physiological astigmatism of 0·5 diopter) the orientation of a light edge is an additional parameter modifying the colour fringes. In case of regular astigmatism, the image of a monochromatic point source takes the form of two line foci in different planes and at right angles to each other.
Chromatic aberration and astigmatism act together to form a point image that is coloured and is circularly asymmetric in its colour composition, irrespective of the accommodation point. This asymmetry leads, on the retina, to an orientation dependence of the colour fringes parallel to edges of white light. In spite of this, subjects with permanently uncorrected astigmatism do not usually see colour fringes in black and white figures (Siebeck 1957). Apparently the CNS is able to take edge orientation as an additional parameter into account in making up its expectation for chromatic fringes.

We now outline some psychophysical experiments demonstrating that astigmatism induced in subjects by ordinary cylindrical lenses can lead to orientation-dependent colour sensations similar to those seen in the McCollough effect. In fact, McCollough discovered her effect during an investigation of prism-induced colour fringes, but she did not investigate the role of eye optics.

2 Experiments and results
Untrained subjects were asked to look monocularly through various lenses at a test pattern (figure 1). The pattern was put on a light grey background at a distance of 2.40 m in front of the subject's eye. The subjects were asked to match the colours to one of a series of Munsell colour plates (matte), seen through the same lenses, which were mounted around the test pattern, with which they shared a common illumination and background. Twenty different equidistant Munsell hues were used, each with a number of different saturations (116 chips). The eyes of all six subjects had previously been tested by an ophthalmologist and corrected if necessary; according to the Ishihara test, they had normal colour vision.

Throughout the experiment each subject wore a frame holding his individual correcting lenses (if any) for one eye and an opaque disc for the other. The additional lenses which were put into the frame all had collinear optical axes. About sixty combinations of convex and concave, and spherical and cylindrical glasses were used. The subjects usually reported contrast differences between the two stripe systems except when the test pattern's diagonal axis coincided with that of the individual's corrected astigmatism. The refractive axis of the cylindrical test lenses was aligned with the stripes in the test pattern. The sequence of tests was random. The subject was not told which of the test lenses was being inserted. After each group of fifteen tests a control was done (normal vision without additional glasses), followed by a pause. Pauses were inserted to avoid training effects. Tests totalled 2–3 h for each subject. No colour distortions were seen with any lens combination in the Munsell plates themselves. In the controls none of the six subjects could see

Figure 1. The test pattern in the orientation used for the subject in figure 2. Stripes were seen with a spatial frequency of 4.2 cycles deg⁻¹. The incandescent lamp (Osram D, 60 W, 220–235 V) produced a light intensity at the test pattern of 40 lm m⁻². Orientations of cylindrical lens axes are denoted in the same way as stripe orientations.
colour or contrast differences in the test pattern. They saw, however, contrast differences and colour with certain lens combinations. Colour was reported to fill the space between dark bars. Colour saturations comparable to those seen after McCollough effect training were seen for a number of different lens combinations. With lenses of a refractive power greater than 1 diopter, colour was sometimes said to be concentrated in fringes parallel to edges.

The results for one subject are shown in figure 2. For different subjects the distribution of colour differs, but qualitatively the picture is the same. The particular choice of the Munsell hues was reproducible within one session and between sessions, even when these were separated by days. Saturation values, however, showed fluctuations. The mirror complementarity about the diagonal of the figure was seen in this and the other subjects only when the test pattern was oriented appropriately with respect to the subject’s astigmatic axis as described above.

Five subjects were tested with cylindric lenses in sodium light (\( \lambda = 589 \) nm). They all reported seeing different colours between the horizontal and vertical black stripes of the test pattern.

![Diagram](image-url)

**Figure 2.** Colours perceived by one of the six subjects (correction sph +0.75, cyl −0.25 A 0°). Abscissa and ordinate correspond to cylindrical lenses with orthogonal refractive axes. On the diagonal are spherical lenses. All other points are superpositions of cylindrical lenses. Refractive values correspond to centres of the squares. Symbols within the squares denote the Munsell hue perceived by the subject. Saturations were determined but are not shown here to avoid confusion of the figure. The upper and lower symbols within the squares correspond to stripe orientations of 45° and 135° in the test pattern. The symbols enclosed in a circle denote for red the same saturation value that was seen by the subject after 15 min of McCollough effect training and for green approximately the same value. Note that points lying mirror symmetrically with respect to the spherical axis show an approximate complementarity.

### 3 Discussion

A precise evaluation of our measurements in terms of eye optics is impossible. Accommodation can not be directly controlled. In addition chromatic aberration (Sivak and Millodot 1974) and astigmatism (Mütze 1953/1954) change with
accommodation in a complicated, largely unknown way. Moreover there are individual variations. Even if these data and the accommodative state and pupil diameter for each test pattern and subject were known, the computation of line spread functions for the different wavelengths would be a disproportionate effort here.

In our experiment some accommodative compensation of test lens refractive power may have occurred. When the subjects were asked to accommodate to one stripe orientation, the intensity of the colour seen in the other stripe orientation was reported to increase.

The main interest in the McCollough effect as an experimental tool is the hope of learning something about those neuronal processes that have to do with picture processing. Line orientation was in this context always taken as a semantic concept, although on a rather fundamental level. The relative ease with which stripe orientation (in distinction to more complicated features) can be associated with colour sensations in the McCollough effect is mostly attributed to the existence of orientation-specific cells in the visual cortex. Eye optics as origin or raison d'être of the McCollough effect was never taken into consideration because the eye is usually regarded in this context as being symmetric around the optical axis. Our experiments show that the slight asymmetries that usually occur in the form of astigmatism are quite sufficient to produce orientation-dependent colour sensations which are comparable to the McCollough effect in intensity and spatial distribution. We do not claim, however, that these colour sensations are entirely of optical origin. Observations made in monochromatic light on phantom fringes, McCollough effect (McCollough 1965), and astigmatism-induced colours (reported here) demonstrate that at least some of the colour phenomena are neural in origin. Our observations made in sodium light may be interpreted as follows. When looking through a cylindrical lens, the eye accommodates to different depths when confronted with different stripe orientations. The CNS therefore expects different colour fringes. As no colours can be present on the retina apart from the monochromatic light, this deviation from expectation is interpreted as colour. According to this interpretation it is to be expected that in short experiments astigmatic subjects would perceive colour fringes when wearing lens combinations correcting the chromatic aberration of their eyes.

Two conclusions may be drawn from our observations. One of them regards McCollough effect experiments. If they are performed to reveal true learning, then two sources of errors must be excluded. Orientation-dependent colours may be influenced both by physical changes between tests and by different parameter settings of the eye (pupil diameter and accommodation) causing the CNS to change expectations. The latter corresponds to the physiological range of behaviour and cannot be regarded as true learning. To exclude such effects, pupil size and depth of accommodation must be kept constant between tests. The former can be done with the help of an artificial pupil. As the latter cannot be controlled directly, all variables influencing it must be paid attention to. In an astigmatic subject accommodation may depend on stripe orientation. It is therefore advisable to use only subjects whose astigmatism is corrected and who are wearing their glasses constantly so that they are in a stationary state. Apart from viewing distance, accommodation is also influenced by small changes in colour temperature of white light illuminating the test pattern. Influences of colour temperature on the McCollough effect have been reported (Stromeyer 1972).

In addition to external controlling factors, any conscious or unconscious accommodation effort by the subject may influence the perceived colour sensations, as we described above. Unconscious changes in accommodation may explain a recent
finding (Jenkins and Ross 1977). The authors report observations on a test pattern similar to ours which show that the McCollough effect “is contingent on subjective changes in the organization of the test pattern. As the organization flips from one state to the other, the colour after-effect switches in and out.”

Our second conclusion is a new interpretation of the McCollough effect. It is only possible to make colour judgements by comparing the retinal image to an expectation formed by experience. This expectation is made up in each instant on the basis of parameter values. Among these must be the orientation of edges so that the system can cope with astigmatism. In the McCollough training the tuning between retinal image and expectation is upset by the persistent association between stripe orientation and colour. In the test situation the changed expectation causes the subject to see colours which are objectively not present. In this interpretation the McCollough effect can be seen in direct analogy to the prism-induced colour aftereffects (Gibson 1933; Kohler 1962).

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