John Mollon: Colourful notions

Studies in scarlet

What is colour? What actually happens when we perceive colours? John Mollon, a lecturer in experimental psychology at the University of Cambridge, looks at some significant experiments in colour vision.

In Paris in the late spring of 1789, Gaspard Monge presented a curious experiment to the members of the Royal Academy. On the wall of a house that faced the windows of the Academy, he had fixed a sheet of red paper. He invited his fellow *académiciens* to look through a piece of red glass and consider the colour of the red paper. The result was as counter-intuitive in 1789 as it remains today.

To those *académiciens* gazing at it through the red glass, one might suppose that the red paper would have looked a peculiarly vivid red—a lurid vermilion hinting at the blood-letting that was soon to touch even the select company of the Academy. But, in fact, the red paper looked white. And white objects also looked white through the red glass. Monge pointed out that the paradox was particularly clear when a complex scene was observed. Conversely, if the red glass were mounted at the end of a narrow tube and the tube were pointed at the red paper so as to exclude all other objects from view, then the paradox disappeared and a vivid red was perceived. This last observation suggested that the phenomenon had its basis in our perception rather than in the physical nature of light.

Technologist and geometer, Monge was a man of unusual clarity of thought. His talents earned him high administrative office under the ancien régime and he was to continue to enjoy the favour of administrations as diverse as the Comité de Salut Public and the First Empire. He realised that the paradox of the red glass was not an isolated illusion. Rather it was a by-product of a fundamental property of our visual perception, a property that normally serves us well and that is today known as *colour constancy*: objects in our world appear to retain an almost constant hue despite large changes in the colour of the illumination. A sheet of white paper, for example, will continue to look white whether we examine it in the yellowish illumination of indoor tungsten light or under the bluish cast of northern daylight. The composition of the light actually reaching our eye from a particular object depends on (*a*) the proportions of different wavelengths in the illumination and (*b*) the permanent tendency of the object to reflect some wavelengths more than others; but our perceptions depend almost exclusively on the latter of these two factors. Our sensations of hue are more stable than we might expect them to be.

Cameras do not yet have the automatic correction that our visual system exhibits. Many readers will at some time have made the error of using 'daylight' film to photograph an indoor scene lit by tungsten light: when our photograph is returned from processing it is little more than a chiaroscuro study in yellows and browns, a very poor representation of what we saw. It was 'colour constancy' that deceived us into supposing that the use of outdoor film would make only a trivial difference.

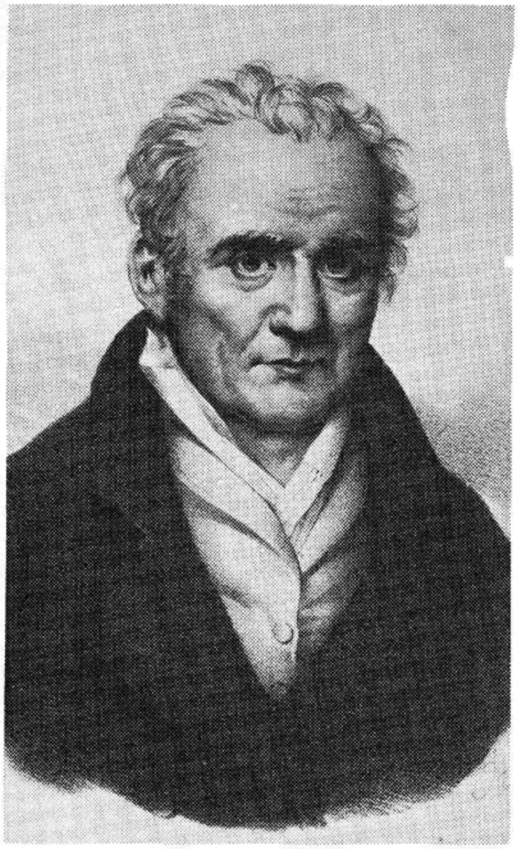
How is this 'colour constancy' to be related to the standard theory of colour vision that we learnt at school? We learnt that our colour vision depends on the cone cells of our retina. There are, the theory went, three kinds of cone, with maximal sensitivities in different parts of the spectrum; and our colour perceptions depend on the ratios in which the different cones are stimulated. As far as it goes, this statement remains completely correct, and in recent years direct measurements have been made of the individual types of cone in the human retina; but the phenomenon of colour constancy shows that there is not a fixed relationship between a particular hue sensation and the proportions of different wavelengths in the light falling on a local retinal region. Monge made the point with extraordinary prescience:

> Ainsi les jugemens que nous portons sur les couleurs des objets ne paroissent pas dépendre uniquement de la nature absolue des rayons de lumière qui en font la peinture sur la rétine; ils peuvent être modifiés par les circonstances, et il est probable que nous sommes déterminés plutôt par la relation de quelques-unes des affections des rayons de lumière que par les affections elles-mêmes, considérées d'une manière absolue.

Whatever is the property of light that causes colour sensations (in 1789 Monge could not know what that property was), it is not the absolute value of this property that determines what hue we see.

Between 1850 and 1950, the phenomenon of colour constancy was repeatedly demonstrated—and its limitations were quantified. There indeed are limits to our ability to make stable judgments of colour. We all know the perils of choosing clothes or furnishing materials in fluorescent light: a green may turn brown when we later see it in tungsten light; and the green fabric that in the shop perfectly matched our sample of green carpet may no longer match when we get it home. Monge's experiment corresponds to the extreme case where the illumination itself is strongly coloured, being confined to a narrow band of wavelengths: to look through a red glass is equivalent to illuminating the scene only with red light. In this case, our visual system does its best and represents white objects correctly, but it has no way of distinguishing between a white object and a red one that reflects to our eye the same proportion of the incident red light. If we are to see good reds, there must be a variation, across the spatial array, in the ratios in which our different types of cone cell are stimulated.

Although colour constancy was well known to those who studied colour vision, it remained in 1958 an esoteric matter, given only a brief and qualitative mention in student textbooks,



Gaspard Monge first demonstrated that objects in our world appear to retain an almost constant hue despite large changes in the colour of the illumination

and quantitatively understood by only a handful of specialists. It was then that the field was shaken up by a man who, like Monge, was both a wealthy technologist and a scientist. This man was Edwin Land, inventor of polaroid and of the instant camera, and President of the Polaroid Corporation.

Typical of Land's striking demonstrations is the following. A black-and-white photograph of a scene is taken through, say, a red filter, and a second photograph of the same scene is taken through a green filter. A positive transparency is made from each of the two negatives. The first transparency is projected on a screen through a red filter; the second transparency is projected in register with the first but not through any colour filter. So we have a pattern of red light falling on the screen from one projector and a pattern of white light from the other. The *edges* of objects coincide in the two superimposed patterns. But, and this is the important point, a light area in one pattern will not necessarily correspond to a light area in the other pattern. For a red object, say, will have produced a light area in the photograph originally obtained with a red filter and a dark area in the photograph originally obtained with a green filter.

So red and white patterns are superimposed on our screen. What should we see? Whites, pinks and reds, one might suppose. Thus the most saturated red should occur where a given patch is very light in the image projected through the red filter and is dark in the black-and-white image from the other projector. Pinks should occur where a patch is of similar lightness in the two superimposed images.

But that is not what Land found. The composite image on the screen exhibited a much richer gamut of colours, which included greens and blues. And an important secondary finding was this: if the overall intensity of one of the two projectors was turned up or down over a large range, then there was very little change in the colour name that observers gave to any given object in the projected scene.

Land's demonstrations attracted widespread public interest. Popular accounts, in newspapers and magazines, concentrated on the possibilities offered by two-colour reproduction in films and television. But Land's own writings emphasised the implications for the theory of colour vision. Although he eschewed the term 'colour constancy', he used words very much like those of Monge to suggest that hue sensations do not depend absolutely on the wavelengths and radiances reaching our eye from a local area of the scene.

> . . .the colour at a point in an image depends on a ratio of ratios; namely, as numerator, the amount of a long-wave stimulus at a point as compared with the amount that might be there; and, as denominator, the amount of a shorter wave stimulus at that point as compared with the amount that might have been there.

In later experiments, Land and his collaborators have been led to direct demonstrations of colour constancy and have introduced a mathematical theory of how our visual system achieves the constancy.

From the scientific establishment Land attracted a largely hostile response. The less insightful critics complained that his effect could be explained by the known phenomenon of 'colour contrast'. The more intelligent commentators realised that Land's effect was generated by the mechanism of colour constancy, but they were rightly angered that he made no acknowledgement of the existing scientific literature. In his most recent theoretical statement, published in 1983, he does relate his 1958 demonstrations to colour constancy, but strangely persists in his complete disregard of earlier work on the topic of earlier theories of how constancy is achieved by our visual system.

How are we to assess Land's excursions into visual science? There is a widespread popular idea that his experiments challenge the mainstream theory of colour vision, a challenge improperly ignored by the scientific establishment. This popular idea is thoroughly mistaken. Land's recent demonstrations, though grand and elaborate ones, are merely re-demonstrations of the classical phenomenon of colour constancy. By not placing his work in the context of existing science, by hinting that he is more of a heretic than he is, he must carry some blame for the neglect of his work by the establishment. But his splendidly illustrated lectures, and the air of novelty that invests them, have excited fresh interest in colour constancy. And his *theory* of how the visual system achieves colour constancy is important: he proposes how, simply from the pattern of light and dark seen by each individual class of cone cell, the visual system could allow changes in the illumination and work out the permanent colours of objects. The idea is that each of the three cone systems independently extracts the spatial pattern of light and dark as seen by that system, scaling each local signal according to the total range of illumination that it finds over a larger region. The latter scaling gives a pattern of lightnesses that is specific to a particular class of cone. Later in the brain, a comparison is made of the three separate lightnesses signalled for the same local area by the three cone systems, and this comparison reliably gives the colour of the corresponding surface. The theory has caught the attention of those who work on artificial intelligence, for it is a paradigmatic example of a 'computational' theory of how the brain might accomplish a particular task. And Land has gained the interest of several leading neurophysiologists, notably Semir Zeki in London and David Hubel at Harvard, who have begun to ask where in the brain are carried out the computations that give us constancy. The establishment and Land are coming together.

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John Mollon took part in the 'Horizon' programme 'Colourful Notions' (BBC2).